MONTHLY WEATHER REVIEW

VOLUME 80 NUMBER 5

MAY 1952

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MONTHLY WEATHER REVIEW

Editor, JAMES E. CASKEY, JR.

Volume 80
Number 5

MAY 1952

Closed July 15, 1952
Issued August 15, 1952

RECENT MONTANA GLACIER AND CLIMATE TRENDS

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[Manuscript received February 25, 1952]

ABSTRACT

Glaciers of Glacier National Park, Mont., the program for their measurement, and findings from measurements and mappings are discussed. Recent trends in temperature and precipitation in Montana are analyzed and their relation to glacier changes are noted. The growth of Glacier Park glaciers in recent years, after over 40 years of recession, appears to be related to the recent cool and relatively wet years in the northern Rocky Mountain Region. It is pointed out that this trend toward cool, wet weather coincides with Willett's tentative forecast [6] based on extrapolation of sunspot–climate relationships.

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INTRODUCTION

There is evidence to show that there are critical points in climatic variations affecting glacier growth or ablation. When such points are reached, the effects on temperate and polar climates can become very large [1, 2]. Many authors (notably Tannehill [3], Kincer [4], Ahlmann [5], among others) have described the world-wide increase in average temperatures which, with only minor fluctuations has occurred during the last 100 years. This gradual temperature increase has coincided fairly well with world-wide (with a few local exceptions) glacier decrease in both area and volume.

Since the relationship of glacier behavior to climatic variations and fluctuations has been established [2], it is the purpose of this paper to discuss the most recent fluctuations in Montana climate in the light of glacier behavior in Glacier National Park in the northwestern part of the State. While the study is limited both in period and area covered, the results appear to agree quite well with Willett's recent extrapolations [6].

Glacier behavior in Glacier National Park has been described by Beatty and Johnson [7]. Grinnell Glacier appears to have followed very well the pattern of decrease in glacier size observed over the world in general for the last 70 to 80 years. In particular, however, Beatty refers to the rapid glacier recession which accompanied the very warm years of the 1930–39 decade, and points out that Grinnell Glacier lost over half its 1902 volume in the succeeding 48 years. However, in their 1951 annual report on Glacier National Park glacier studies, Beatty and Johnson describe the first sizable increase in the size of Grinnell Glacier in 40 years—an increase of the order of 5 feet in depth near the front, with greater depth increases probably farther back from the front. They also reported, at the same time, an average advance of 10 to 25 feet of the front edge of this glacier. A comparison of the behavior of this glacier with weather records for Montana, including meager information about precipitation in the glacier area, furnishes some interesting results which are presented in the following sections.

GLACIERS OF GLACIER NATIONAL PARK

GEOGRAPHY AND GEOLOGY

Glacier National Park lies astride the Continental Divide in the Rocky Mountains of northwestern Montana adjoining the international boundary between Canada and the United States. The park was established by act of Congress in 1910 and comprises close to one million acres of federally owned land.

It is essentially a land of rugged mountains formed by great earth forces. Here is found one of the classic examples of faulting—the Lewis Overthrust, where a section of the earth's crust was uplifted along a gigantic break and then pushed northeastward for a distance of some eighteen miles. More recently Ice Age glaciers played their part in sculpturing the landscape which in general appearance today is said to resemble that of the Swiss and Italian Alps.

In this magnificent mountain setting are more than 200 lakes, mostly of glacial origin, and 50 small glaciers of the cirque or cliff type. These glaciers are not considered remnants of the large Ice Age valley glaciers which in some instances extended out on the Great Plains to coalesce with the Continental Ice Sheet. Evidence indicates that the present glaciers are of a more recent origin.

EARLY RECORDS OF PARK GLACIERS

The first scientist to see and record the presence of a glacier in the area that is now Glacier National Park was Professor Raphael Pumpelly, who journeyed over Cut Bank Pass in 1883 and saw the glacier now named in his honor. George Bird Grinnell, an editor of *Forest and Stream* magazine and a prominent sportsman and conservationist, visited the area in the early eighties and mapped much of the area on the east side of the Divide. It was Grinnell who, in 1887, first visited the glacier now bearing his name. Other scientists such as Dr. Lyman B. Sperry and Professor L. W. Chaney, Jr., followed in the nineties and likewise discovered and visited the ice bodies now named for them.

Field parties of the United States Geological Survey mapped the greater portion of the area between 1900 and 1904, and the present topographic map of the park shows the glaciers as they then existed. Dr. William C. Alden [8], of the United States Geological Survey, made the first comprehensive study of the geology and the glaciers during the summers of 1911–13 and estimated that there were about 90 small glaciers ranging in size from Blackfoot Glacier (included Jackson Glacier, which is now separate and distinct), with its 3 square miles of ice, down to masses but a few acres in extent yet exhibiting the characteristics of true glaciers.

Dr. James L. Dyson [9] computed the areas of some of the major glaciers at the time they were first mapped by the United States Geological Survey from the topographic sheets and from early day photographs which showed the approximate locations of the glacier borders. Several of these individual glaciers at that time apparently had surface areas exceeding 1 square mile. From photographs taken during that period, it appears that these glaciers abutted their terminal and lateral moraines, indicating they were near their maximum size. The size of the moraines in turn would indicate that the maximum stage carried back into the late 1800's, probably reaching a peak around 1890.

PRESENT DAY GLACIERS

Of the 50 small glaciers existing today in the park, only 1 has a surface area of nearly one-half square mile and not more than 7 others are over one-fourth square mile in area. These glaciers are to be found in shaded locations on east- or north-facing slopes at elevations between 6,000 and 9,000 feet, well below the regional snowline.

During the 60-year period following the first written or photographic records of these glaciers, all have been rapidly depleted in both area and volume. Many of the glaciers shown on the topographic map of the park (completed in 1914) are no longer in existence, and others are either inactive or too small to be considered true glaciers. Agassiz Glacier, for example, when first mapped by the United States Geological Survey in 1902, had an area of about 1.4 square miles, and for several decades was considered to be the largest in the park. By 1940 it had shrunk to a position of relative unimportance with a surface area of less than 0.3 square mile, and to all intents, was inactive. Several glaciers in the park occupying similar terrain have likewise wasted away much more rapidly than those occupying normal cirques.

PROGRAM OF MEASURING PARK GLACIERS

Since 1931 the National Park Service has carried on a program of glacier measurement studies in a number of the western national parks in cooperation with the Committee on Glaciers of the American Geophysical Union. These studies, as applied to Glacier National Park, have consisted of marking the fronts of four of the larger glaciers each year to determine the advance or recession of the ice fronts and, more recently, the surface mapping of these glaciers to determine volume loss and rate of movement.

From 1932 to 1944 inclusive, recession of the fronts was determined by direct measurements from fixed points adjacent to the glacier or from paint marks indicating the location of the front in previous years. In addition, Dr. James L. Dyson, serving as a seasonal ranger naturalist in the park, undertook the job of mapping the surface areas of Grinnell Glacier (1937), Sperry Glacier (1938), and Jackson Glacier (1939) by means of a plane table, telescopic alidade, and stadia rod. From these maps Dyson was able to determine the approximate loss in surface area since they were first mapped by the United States Geological Survey. By extending profiles from the terminal moraines he was also able to estimate the loss of

volume in the ice mass itself during the same period. Results of these studies indicated that all glaciers of the park had lost more than 50 percent of both area and volume in the period from 1900 to 1940.

Starting in 1945 a change in the method of measuring the ice fronts was put into effect by the new park naturalist, M. E. Beatty, with the assistance of Arthur Johnson, of the United States Geological Survey, Water Resources Branch, Tacoma, Wash. This method was to map the entire front of the Grinnell, Sperry, and Jackson glaciers by plane table and stadia rod, thus giving a better and more accurate average than could be obtained from one or two fixed points which might not be representative of the entire glacier.

In addition to mapping the fronts, profiles were run across the glaciers to determine changes in the surface level of the ice, and large boulders were located to give some indication as to the rate and direction of movement of the ice. Plans called for the complete surface mapping of these glaciers at 5-year intervals, but lack of funds, personnel, and favorable weather conditions have hampered the program.

In 1950 a program of aerial mapping by photogrammetric methods was instituted as a result of donations by the American Geographical Society of New York and the Glacier Natural History Association, supplemented by Glacier National Park funds. Arrangements were made with the United States Forest Service in Missoula to take the aerial photographs and put in the necessary ground controls on a repayment basis. Funds were sufficient to have photographs taken of over 30 park glaciers, put in ground controls for 3, and to prepare a surface map of Jackson Glacier. Unsuitable weather prevented continuation of this program in 1951, but the United States Geological Survey in Washington offered to prepare surface maps of the other two glaciers having ground controls, using aerial photographs taken in 1950.

SUMMARY OF FINDINGS FROM MEASUREMENTS AND MAPPING

All glaciers experienced rapid recession of fronts and shrinkage in area and volume between 1902 and 1940, with only moderate recession and area loss between 1945 and 1950.

TABLE 1.—*Summary of measurements and mappings of Sperry and Grinnell Glaciers*

	Sperry Glacier	Grinnell Glacier
First measured (year)	1935	1932.
Last measured (year)	1950	1951. [3]
Net recession during period	about 800 feet in 15 years	about 610 feet in 19 years.
Average yearly recession	53 feet per year	32 feet per year.
Area in 1900–02 [1]	840 acres (approximate)	600 acres (approximate).
Area in 1950 [2]	300 acres (approximate)	
Area in 1951 [2]		270 acres (approximate).

[1] Computed from Chief Mt. Quad., U. S. Geological Survey.
[2] Estimated from surface mapping.
[3] Ice front showed an advance for first time in 1951.

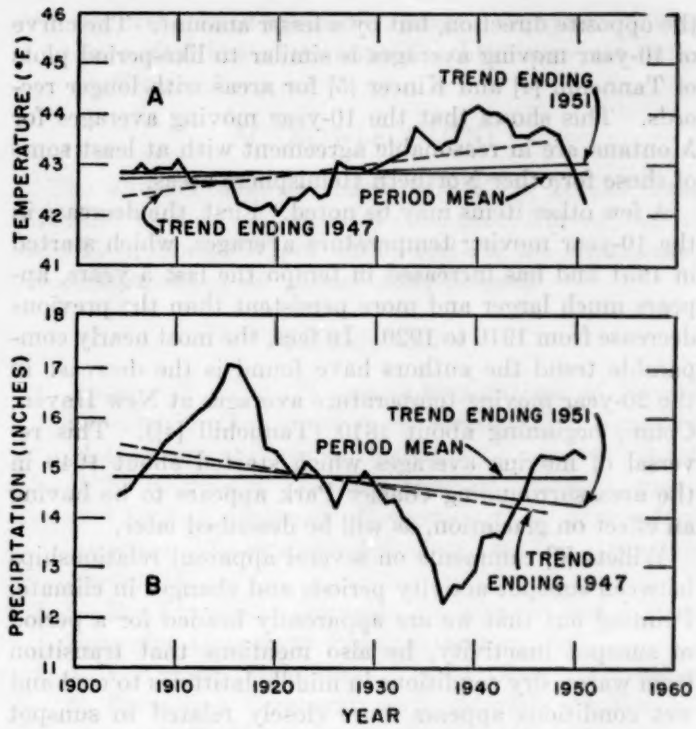

FIGURE 1.—Montana temperature (A) and precipitation (B). Ten-year moving averages (irregular solid curve) ending with year indicated by abscissa, mean for the period (horizontal solid line), straight line trend ending 1947 (dashed line), straight line trend ending 1951 (thin solid line).

Movement of ice mass (rate of motion) was found extremely variable based on measurement of movement of rocks imbedded in ice surface. The maximum rate is considered to be about 40 feet per year.

All glaciers lost at least 50 percent of their surface area in the 50-year period following the turn of the present century; some lost as much as 80 percent, and several disappeared entirely.

Table 1 summarizes findings from measurements and mappings of the Sperry and Grinnell Glaciers.

RECENT TRENDS IN MONTANA CLIMATE

The last 57 years of Montana average temperature and precipitation records have been used for comparison with glacier measurements. The records for the whole State area of about 147,000 square miles are used to minimize local effects. In figure 1 are plotted 10-year moving temperature and precipitation averages for Montana, ending with the year indicated by the abscissa. Means for the period of record are shown. By the method of least squares (see Croxton and Cowden [10]), straight line trends were computed for the period ending with 1947 and for the period ending with 1951. These trend lines also are shown in figure 1.

It will be noted that the temperature trend line slope decreased to an insignifica it value from 1947 to 1951, while the slopei n the precipitation trend line changed in

the opposite direction, but by a lesser amount. The curve of 10-year moving averages is similar to like-period plots of Tannehill [4] and Kincer [5] for areas with longer records. This shows that the 10-year moving averages for Montana are in reasonable agreement with at least some of those for other Northern Hemisphere areas.

A few other items may be noted. First, the decrease in the 10-year moving temperature averages, which started in 1951 and has increased in tempo the last 5 years, appears much larger and more persistent than the previous decrease from 1910 to 1920. In fact, the most nearly comparable trend the authors have found is the decrease in the 20-year moving temperature averages at New Haven, Conn., beginning about 1810 (Tannehill [4]). This reversal of moving averages which started about 1940 in the area surrounding Glacier Park appears to be having an effect on glaciation, as will be described later.

Willett [6] comments on several apparent relationships between sunspot activity periods and changes in climate. Pointing out that we are apparently headed for a period of sunspot inactivity, he also mentions that transition from warm, dry conditions in middle latitudes to cool and wet conditions appears more closely related to sunspot activity than the emergence from cool wet to warm dry conditions. It was Willett's suggestion that the rainfall increase associated with such a change has already appeared in the western United States, and it is considered possible that the expected accompanying temperature change may also be at hand, in view of the trends shown for Montana. The evidence certainly shows that Montana has tended toward wetter and colder climate now for several years, but the persistence of such a trend remains impossible to predict in spite of the fact that it appears established. Moreover, in climatic trends of many years which are available for study, an occasional year has been encountered which was an exception to the general pattern. Paramount, of course, is the fact that our historical knowledge of most of the factors is very limited. In his work, Willett pointed out that sunspot activity records may be used roughly from about 1750, but have become fully reliable only during the last 100 years. Climate records are of similar quality but when we consider records of 100 to 200 years against climate history as a whole, our basis for study is limited indeed. We know there was agricultural activity in Greenland in the years around 1300 or 1400 A. D. [5], but direct observations of sunspot activity, precipitation, temperatures, etc., are missing.

At any rate, Montana has for about 11 years been riding a trend toward a comparatively cool wet climate. Where this trend will lead or when it may be reversed are matters apparently undeterminable at this time. Willett, however, has made a tentative forecast which ties in well with the observed Montana trends, and indicates the trend may last for several decades. While such a trend has not definitely appeared in some parts of the Northern Hemisphere, Willett mentioned a probable lag of several years in some European and Asiatic areas. Brooks [2] also indicates the strong likelihood that we are now in a period of climatic change which may have far-reaching effects upon civilization. The complete change may take thousands of years, however, if glacier research and the history of the earth have been interpreted correctly.

RECENT GLACIER CHANGES IN RELATION TO CLIMATE

A sizable advance and increase in depth of Grinnell Glacier occurred during the season ending in mid-1951, when an advance from 10 to 25 feet and a depth increase of 5 feet near the front were measured [11]. This was apparently the first sizable increase since 1910, when the park was created, and follows a period of about 3 years during which changes were small. Although actual glacier measurements were started in 1932, attempts to record climate factors did not begin until late in August 1949, when the United States Weather Bureau installed a storage seasonal precipitation gage, and the United States Geological Survey started measuring run-off from the Grinnell Glacier drainage area. Run-off and precipitation data are shown in tables 2 and 3. Run-off values are from 85 to 90 percent of the measured precipitation, assuming precipitation to be reasonably uniform over the basin. Loss from seepage should be small in such a geological formation; therefore, the precipitation which did not run off can be assumed either to have evaporated or to have contributed to glacial growth. That which contributed to glacial growth may show up in run-off excess over precipitation should ablation occur during the period of measurements. In any case, both precipitation and run-off records, when coupled with glacier measurements over many years, should give results of great usefulness in future studies of glacier behavior.

Amounts measured for two seasons, and verified by run-off measurements, indicate precipation in the glacier area to be unusually heavy for an interior North American location at this latitude (48° 46′). At the same time,

TABLE 2.—*Run-off from Grinnell Glacier Basin (3.4 sq. mi.). (U. S. Geological Survey)*

Month	Year ending Sept. 30, 1950		Year ending Sept. 30, 1951 [1]	
	Inches	Acre-feet	Inches	Acre-feet
October	3.79	687	10.71	1,940
November	4.17	758	4.23	770
December	1.44	261	2.85	516
January	.34	61	.71	128
February	.31	56	.62	113
March	.48	83	.42	76
April	2.05	373	4.43	803
May	10.44	1,800	16.26	2,950
June	32.02	5,820	19.30	3,500
July	29.74	5,290	24.33	4,410
August	15.10	2,750	11.99	2,160
September	6.66	1,210	9.13	1,650
Water Year	106.54	19,339	104.98	19,016

[1] Unpublished records, subject to revision.

TABLE 3.—*Precipitation totals for Grinnell Glacier, Summit, and Babb, Mont.*

Period	Grinnell	Summit	Babb
	Inches	*Inches*	*Inches*
Aug. 27, 1949–July 20, 1950	125.1	50.2	18.4
July 20, 1950–July 24, 1951	117.5	52.0	28.4
July 24–Sept. 12, 1951	8.7	4.3	7.2

precipitation was unusually heavy at Summit, about 33 miles south-southeast of Grinnell, and at Babb, about 21 miles northeast (see table 3). While low temperature is considered the main element in glaciation by Ahlmann [12], and probably must be assigned the primary role in the over-all history of a glacier, there seems to be some basis for considering the importance of heavy precipitation to glaciation. It would seem that during periods when temperature might remain near or below freezing most of the time, temperature fluctuations might be considered of secondary importance to precipitation. Also to be considered are inherent differences between the so-called maritime glaciers of the Northwestern European Coast and the continental glaciers of North America.

SUMMARY AND CONCLUSIONS

1. After 40 years or more of recession, Glacier Park glaciers seem to have entered a period of growth, probably resulting from the several recent cool and relatively wet years in the northern Rocky Mountain Region.
2. Montana temperatures, at least for the last 11 years through 1951, show a marked downward trend. The average for the 10 years ending with 1939 was 44.1° F., but for the 10 years ending with 1951, this average was only 42.2° F. A similar trend, but in the opposite direction, shows up in precipitation records.
3. Willett's tentative forecast of a trend toward a cool wet cycle in middle latitudes coincides very well with observed conditions in the Northern Rockies during the 2 years following his work. However, there seems to be insufficient basis for concluding that the observed trend will continue, maintain itself at the present level, or reverse.
4. The program of glacier research in Glacier Park has been enhanced by the addition of precipitation and run-off measurements in the Grinnell Glacier basin. More details of glacier behavior will become apparent as more records become available for study. Development of these details will undoubtedly help to cast light upon some of the questions not yet fully answered in studies to date. Of course, these glacier studies will have their impact on the study of long-range climate variations.
5. From Dr. C. E. P. Brooks, [2] we quote a sentence which sums the case quite well: "The problem is not entirely academic, for signs are not wanting that we are even now in a period of climatic change which may have vital, but so far unpredictable, consequences for civilization."

ACKNOWLEDGMENT

The authors wish to thank Mr. C. S. Heidel, Staff Engineer of the United States Geological Survey, for his help in providing run-off data, and for his enthusiastic encouragement of the glacier study project.

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THE WEATHER AND CIRCULATION OF MAY 1952[1]

Including a Study of Some Recent Periodicities

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GENERAL CIRCULATION CHARACTERISTICS

The mean circulation pattern for May 1952 was characterized by low zonal index and blocking activity from central Europe westward through North America. These conditions were accompanied by a large area of persistently above-normal 700-mb. heights extending from Scandinavia to central Canada (fig. 1) and a strong narrow band of westerlies at lower latitudes (south of 40° N.) across the Atlantic sector. Along this narrow channel, the strongest 700-mb. jet on the map (fig. 2), moved almost all of the cyclones which passed eastward off North America (fig. 3 and Chart X). Only a few of these storms ever completed the customary northeastward trajectory to the Greenland-Iceland area. Most were shunted eastward, far south of the normal path, in the area of below-normal 700-mb. heights (fig. 1). Many of these stalled and filled in the central Atlantic as a result of the prevailing blocking regime. This characteristic is in accord with the findings of Rex [1] who showed that May is an especially favored month for blocking activity.

[1] See charts I–XV following p. 93 for analyzed climatological data for the month.

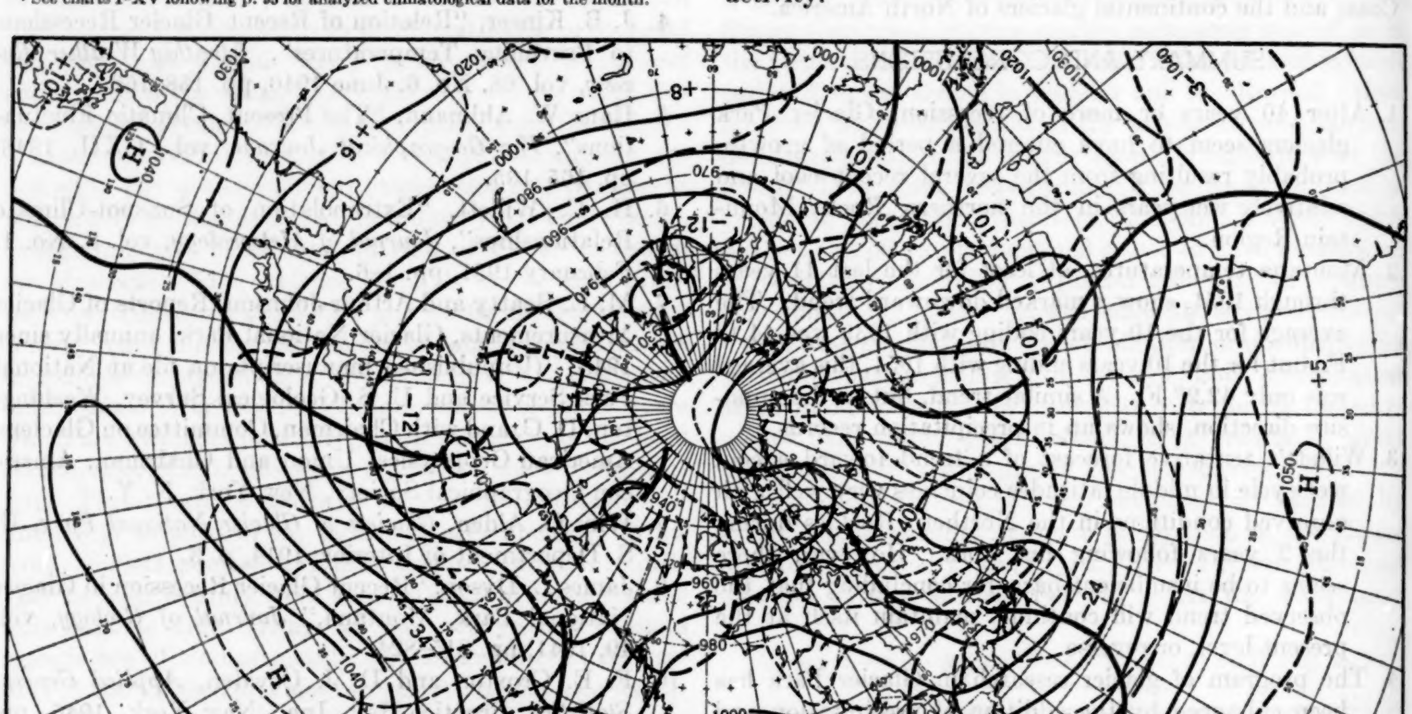

FIGURE 1.—Mean 700-mb. chart for the period April 29—May 28, 1952. Contours at 200-ft. intervals are shown by solid lines, intermediate contours by lines with long dashes and 700-mb. height departures from normal at 100-ft. intervals by lines with short dashes with the zero isopleths heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

The western Atlantic was thus the scene of the strongest trough and ridge activity on the map. The warm blocking High in the Davis Strait had the greatest 700-mb. height anomaly (+400 ft.) observed in the Northern Hemisphere. At middle latitudes, in the trough south of Newfoundland, heights averaged 240 feet less than normal. This trough was some 10° to 15° of longitude farther east than its counterpart in April [2]. The major eastern Pacific trough (fig. 1) was also slightly farther east in May (about 5° in middle latitudes) than the analogous April feature, so that the large-scale patterns had some similarity during the 2 months. However, the low-latitude segment of this trough, near the Hawaiian Islands, was much farther west than the trough off California in April. Consequently, the prevalence of blocking activity, which augmented the seasonal weakening of the westerlies, and the increasing wave length, as the lower latitude troughs separated, favored a new trough development. In May such a new trough development did take place, from the Central Plains of the United States southward, and it became more conspicuous as the month progressed.

The eastern Pacific trough was accompanied by stronger than normal cyclonic activity (below-normal heights, fig. 1, below-normal sea level pressures, Chart XI inset) and was associated with a well-marked westerly jet stream (fig. 2). This stream, while traversing the western North American ridge, did not show the well-defined split into two parts which was noted in April. Instead, it appeared to disintegrate over the continent, with three weakly marked maxima penetrating the ridge. Its re-establishment and emergence from eastern North America was closely associated with the strong confluence of warm and cold air streams over the eastern United States. Some evidence of the thermal characteristics of this mechanism is afforded by the surface temperature anomalies of the eastern United States; Charts I-A and I-B illustrate the much stronger than normal thermal contrast between New England and the southeastern States.

CYCLONE AND ANTICYCLONE TRACKS IN RELATION TO THE MEAN CIRCULATION

Weather systems entering North America from the Pacific were subjected to the influence of the western North American ridge. Only one storm center penetrated the western United States at lower latitudes, traveling eastward north of the weak southern jet shown in figure 2. Farther north, however, several perturbations did manage to cross the Rockies and set off cyclogenesis in northeastern British Columbia and northern Alberta as illustrated by the cyclone frequencies in figure 3. This illustration, showing the major areas of cyclonic activity and axes of storm movement, indicates that Alberta Lows moved either east-southeastward or south-southeastward. The former motion gave rise to the major east-west storm track of south central Canada, which split abruptly over eastern Hudson Bay as the storms came under the influence of the blocking regime near the lower Davis Strait. The south-southeastward moving Alberta Lows entered the United States by way of the Northern Plains, after which both they and their secondaries moved eastward through the weak trough in the Central Plains, across the eastern Lakes, and were finally filled or turned southeastward by the strong northwesterly flow over New England. The lack of cyclonic activity in the warm blocking ridge just south of Greenland is especially noteworthy since this area is seldom so free of storms at this time of the year.

The anticyclonic activity over North America had two apparent phases. Most of the Highs which affected the United States were of distinct maritime origin (see Chart IX) and entered southern British Columbia from the eastern Pacific. They then moved eastward and east-southeastward through southern Alberta, around the upper level ridge, entering the United States through the Dakotas. Their further collective trajectories were ill-defined in the trough area of the mid-United States, but a preferred exit path by way of the eastern Lakes and southern New England was evidenced. The second phase of the anticyclonic activity centered about the Highs of Polar continental origin whose locus of activity appeared to be north-central Canada, south of the northernmost jet (fig. 2) and south of the northernmost storm track (fig. 3). None of these centers entered the United States (Chart IX) although frequent reinforcement of the mP Highs by cP air was evident. Most of these continental anticyclones followed a trajectory eastward and finally merged with the mean blocking high pressure over the Davis Straits and Greenland.

ANOMALIES OF TEMPERATURE AND PRECIPITATION IN THE UNITED STATES

The month of May was predominantly warm. This was particularly true of the early period, before the mid-United States trough developed. Thus the first week of the month had temperatures averaging as much as 15° F. above normal in the Central Plains and effected such rapid drying in the recently flooded Missouri Valley that many fields deemed lost for the season were expected to prove arable. However, the development of the trough in the United States, and the surges of maritime air which followed the accompanying depressions, produced cooler temperatures in the middle and south-central United States areas. This activity, combined with the cloudiness attending the trough development, was sufficient to bring below-normal temperatures to Texas with near normal temperatures northward and northeastward through the Ohio Valley (Charts I-A and I-B). The coldest (relative to normal) area of the country was the Northeast which was dominated by the strong northwesterly flow comprising the cold segment of the confluent streams. Monthly average temperatures as much as 4° F. below normal were reported from eastern New York to northern

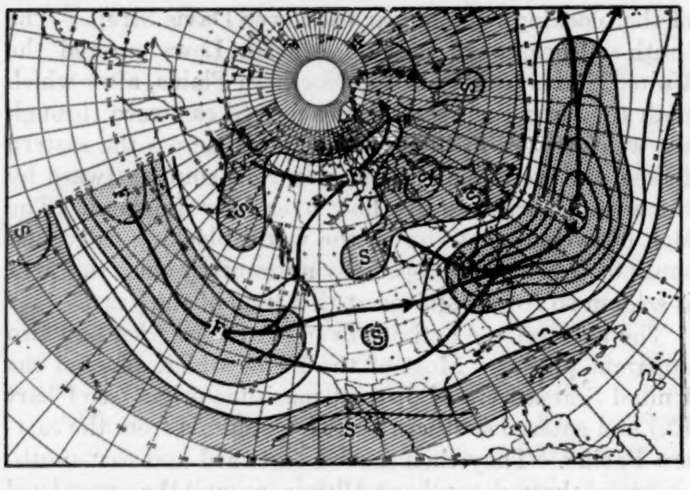

FIGURE 2.—Mean geostrophic (total horizontal) wind speed at 700 mb. for the period April 29–May 28, 1952. Light solid lines are isotachs drawn at intervals of 2 m. p. s., while the heavy solid lines delineate the axes of maximum wind speed (jets). Areas with speeds in excess of 8 m/sec. are stippled while those with less than 4 m/sec. are hatched. Centers of maximum and minimum wind speed are labeled "F" and "S" respectively.

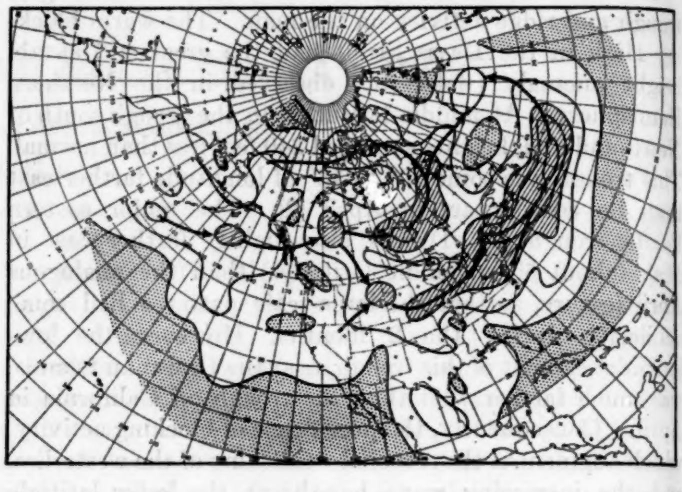

FIGURE 3.—Geographical frequency of tracks of cyclones observed during month of May 1952 within approximately equal area boxes of size 5 mid-latitude degrees of longitude by 5° of latitude. The isopleths are drawn at intervals of 2; areas of zero frequency are stippled, and areas with frequencies of four or more are hatched. The principal cyclone tracks are indicated by solid arrows and are not drawn through the centers for clarity. All data obtained from Chart X.

Vermont and were in part due to the above-normal cloudiness accompanying the overrunning and heavy precipitation north of the prevailing confluence and frontal zone. However, foehn warming east of the Appalachians and the weakness of the sea breeze regime were probably responsible for the above-normal temperatures at coastal stations of New England and the Middle Atlantic States.

The western United States had generally above normal temperature with extremes averaging $+6°$ F. in the lower Colorado and Gila River Valleys. This entire area was one of above-normal 700-mb. heights and abnormally strong upper level anticyclonic circulation (fig. 1) which replaced the more normal lower California coastal trough. Most of the southeastern United States was under a weakly anticyclonic westerly regime which made up the warm component of the confluent streams. Temperatures were consequently above normal despite the fact that 700-mb. heights were slightly below normal and that the anomalous flow was weakly from the northwest.

There were two conspicuous almost zonal bands of above-normal precipitation (Charts II and III). The first or northern band stretched from southern Montana and Wyoming eastward to Iowa, weakening over Illinois, but becoming well marked again from Ohio eastward to the Atlantic Coast and northeastward over New England. The precipitation in the Northeast was about that expected on the cool side of a confluence zone where cyclonic and frontal overrunning theoretically reach a maximum. The western section of the northern band of heavy precipitation accompanied the cyclonic activity and cool air invasions already described. Most of this precipitation occurred around the middle and latter portions of the period as trough conditions in the United States became more dominant.[2] The northern precipitation band was closely aligned with the axes of both the weak 700-mb. jet (fig. 2) and the major storm path (fig. 3).

The second or southern band of above-normal precipitation was chiefly apparent from east Texas eastward across the northern Gulf States to the Georgia coast, with possibly a westward extension in central New Mexico. Gulf precipitation was mostly of the air-mass shower type with a few tornadoes and hailstorms reported. Frequently the activity was associated with warm sector squall lines which accompanied cyclones moving eastward along the main track farther north (fig. 3) The shower activity in New Mexico was most notable as the period ended and the ridge in that area finally weakened. In general, however, the ridge was an effective suppressor of precipitation, and light amounts (or no rain) were observed over most of the Far West and Southwest. Subnormal precipitation, was also observed in the North Central States, in connection with the northwesterly flow east of the mean ridge and the anticyclonic relative vorticity which prevailed at 700 mb. One of the most striking features of Chart III is the zonal band of below-normal precipitation from Kansas to North Carolina, completely separating the two bands of above-normal precipitation to the north and south. This pattern may be related to the split in the westerly jet-stream at 700 mb. (fig. 2).

Over large portions of the nation, the weather was mostly mild and precipitation generally sufficient for agricultural needs. Most areas were reporting excellent farm work progress and favorable growing conditions. Preliminary estimates foretold one of the bumper wheat crops. However, individual areas differed widely and, as often is the case, some localities were suffering acutely from the weather's vagaries; Huron, S. Dak. had the driest May since 1940; Crookston, Minn., the driest since 1917; while Texas was reporting that drought conditions

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[2] An adjacent article by Chapman and Carr describes some of this activity in more detail.

were nearly erased in all sections for the first time in 2 years.

A STUDY OF SOME RECENT PERIODICITIES

One of the more interesting and newsworthy aspects of the weather of this month and for some preceding weeks was the succession of rainy weekends which occurred in the eastern United States. On May 25 the New York City Office of the United States Weather Bureau recorded 1.42 inches of precipitation and the fifth rainy Sunday out of the last six. The meteorological observatory at Blue Hill, Milton, Mass., reported precipitation on three of the four Sundays in May with two of the Sundays completely overcast. Washington, D. C. had a similar succession of disappointing weekends, and so did most of the intervening and adjacent areas. Remembering recent discussions [3] of claims of augmentation and control of 7-day weather periodicities through appropriate silver iodide seeding, many wondered if such seeding was still being practiced. As far as could be determined, no comparable periodic seeding was currently under way; indeed, it seems likely that the use of silver iodide generators has become so common and uncontrolled that the effects of additional periodic seeding would be more difficult than ever to detect. However, periodicities in the weather have been noted for a long time and it seemed advisable to examine the recent data and test its periodic nature.

One method of studying 7-day periodicities is to utilize four complete cycles (28 days). Hence, the tests for May included the first 28 days of the month. A sample array of the 24-hour precipitation totals (ending 2400 EST) at the Washington City Office for the first 28 days of May is shown in table 1. The totals show a striking preference for precipitation to occur on Sunday with decreasing amounts on either side and no measurable precipitation on Wednesday and Thursday.

TABLE 1.—*Accumulated 24-hour precipitation amounts (inches) during first 28 days of May 1952 at Washington, D. C. (city office)*

	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
					T	0	0
	0.29	0.20	T	0	T	.02	.15
	.69	.57	T	0	T	.04	.06
	0	.43	.65	T	0	0	.29
	1.69	0	0	0			
Totals	2.67	1.20	.65	T	T	.06	.50

The analysis was made by a technique commonly employed in testing for periodicities with data composed of a limited set of discrete values [4]. It consisted of fitting a simple cosine curve to the data in such a fashion as to minimize the square of the deviations (of the fitted curve) from the observed values. The 7-day periodic element was then expressed

$$Y=A \cos \frac{360}{7}(x-\theta)$$

where Y=the precipitation in inches (expressed as departure from the mean) for the particular day of the week designated by x

A=the amplitude of the fitted curve in inches of precipitation

x varies from 0, 1, 2, . . . 7 corresponding to Sunday, Monday, Tuesday, . . . Sunday

θ=phase angle expressed in units and tenths where each unit represents a day of the week and Sunday is taken as 0, i. e., Tuesday is 2.0, Wednesday is 3.0, etc., and Sunday is 7.0 or 0.

The cosine function was chosen since θ, the phase angle, would then indicate the day of the week when the precipitation expressed by the equation would be a maximum. For example, if θ is 2.0 the expression $A \cos (x-\theta)\frac{360}{7}$ will be a maximum when $x=2$, since the $\cos 0°=1$, and Tuesday would be the day when, according to the fitted curve, the maximum precipitation would fall. The amounts of precipitation indicated for each day of the week by the fitted curve were correlated in two ways with the observed data: (1) Correlation (R_7) with the average precipitation for each day of the week, and (2) correlation with the appropriate individual daily amounts for each of the 28 days (R_{28}). The latter is the more critical criterion since it relates the periodic function with each day and indicates whether cyclical indications given by the totals were due to a periodicity consistent in amplitude and phase during the entire period or were due to a few sporadic and fortuitously timed large precipitation amounts occurring on several days of the period.

The following array (table 2) presents the results of such analyses for the first 28 days of May 1952. The stations are tabulated from west to east so that spacial comparisons of phase are facilitated. The amplitudes and R_7 factors are of appreciable dimensions; furthermore, the R_{28} values (especially that for Washington, D. C.) are larger than those usually encountered in chance distributions. Specifically, the probability of the Washington value having occurred by chance from a random distribution is about 1 or 2 in 100. It is also of interest to see if the stations progressively farther east showed a sensible progression of phase, as would be expected from eastward-moving perturbations. This did prove to be the case; i. e., the maximum precipitation at Omaha was

TABLE 2.—*Amplitude, correlations, and phase angle values computed from precipitation data for selected stations for May 1–28, 1952. (All values are based on 24-hour precipitation totals ending 2400 EST except Omaha which ends 2400 CST)*

Station	A	R_7	R_{28}	θ
Omaha, Nebr. (Muncie Airport)	.185	.854	.437	4.1
Lansing, Mich. (Capital City Airport)	.183	.766	.316	4.5
Cincinnati, Ohio (Abbe Observatory)	.166	.777	.474	6.6
Washington, D. C. (City Office)	.267.	.848	.529	0.4
Atlantic City, N. J	.282	.638	.453	0.3
New York, N. Y. (Battery Pl. Office)	.251	.612	.449	0.3
Boston, Mass. (Logan International Airport)	.171	.900	.418	0.9

on Thursday (plus 1/10 day); at Lansing, halfway between Thursday and Friday; at Cincinnati, about halfway between Saturday and Sunday; at Washington, almost halfway between Sunday and Monday, etc. These phase-space relations (with the exception of Lansing) are in good agreement, especially since single-station precipitation data were used. It seems pertinent to point out that the periodicity in May 1952 precipitation at Washington, D. C. was greater than that noted at Washington in April and May of 1950 when periodic seeding was being practiced [3].

While a 7-day periodicity was definitely present in the May 1952 precipitation, an appraisal of its probability is more complex. The figures quoted above refer to chance occurrences from a random distribution but most meteorological elements are not randomly distributed. Since the evaluation of periodicities in serially corrrelated data is theoretically difficult, the practical procedure is to examine the past records for other occurrences or periodicities with which the current one can be compared [5]. For these purposes April and May precipitation records since 1919 for Washington, D. C., were examined for similar periodicities in the precipitation data. Analyses of 66 months (the Aprils and Mays for 33 years) revealed no periodicity with an R_{28} as high as that for May 1952. They also indicated that the serial correlation in these precipitation data is so small that the assumption of a random distribution gives approximately the correct results, i. e., the analyses indicated that periodicities equal to that of May 1952 may be expected to occur (during April or May) about 3 times in 100.

Next an evaluation of the recent free–air temperature periodicities was made since, in the past, this element has yielded the more striking results [3, 5, 6]. The following findings (table 3), all that could be processed in the time available, are for the 2200 EST 700-mb. temperatures in ° C.

TABLE 3.—*Amplitude, correlations, and phase angle values computed from 700-mb. temperature data (2200 EST) for selected stations* [1]

Station	Month (1952)	A	R_7	R_{28}	θ
Nantucket, R. I.	May	1.860	.872	.282	-------
Dayton, Ohio	May	1.519	.711	.287	-------
Joliet, Ill.	May	1.475	.803	.256	-------
Omaha, Nebr.	March	2.310	.904	.346	0.0
Omaha, Nebr.	April	3.077	.993	.545	1.1
Omaha, Nebr.	May	1.574	.638	.252	-------
Washington, D. C.	March	2.399	.947	.325	1.8
Washington, D. C.	April	.543	.390	.094	-------
Washington, D. C.	May	.470	.416	.107	-------

[1] These data have been analyzed without removal of the seasonal trend.

It is, at first glance, rather disconcerting that May, the month of notable precipitation periodicity, should be lacking in significant temperature periodicities. This is particularly true at Washington, D. C., where the precipitation periodicity seemed to reach a maximum. Rather surprising in contrast are the March and April 7-day cycles at Omaha and that for March at Washington. The most significant periodicity is that shown by the April Omaha data. While it does not equal the past record periodicities [7] in either amplitude or closeness of fit (R_{28}), it still remains one of the more significant periods of record. The most curious aspect of these Omaha cycles is a tendency, pointed out by both Brier [7] and Hall [5], for the phase of the well-marked periodicities to cluster about Sunday and Monday. Further data collection and testing are necessary to prove the phase preference is real. Meanwhile it presents a stimulating subject for speculation.

The relation of periodicities to the mean circulation patterns is also of interest. It is rather remarkable that the majority of the marked periodicities studied recently in the United States have occurred in spring. An inspection of the circulation features which prevailed during some of these periodicities reveals a tendency for them to occur where the mean 700-mb. pattern indicates a fairly flat flow of westerly or zonal type often with slight cyclonic curvature and usually without marked confluence or diffluence. It may well be that the May 1952 confluence over the Middle Atlantic States augmented the usual rainfall regime, i. e., through increased overrunning of the cold flow by the periodic perturbations from the mid-United States, and that the temperature periodicities were disturbed and masked by the same cool northwesterly flow. In the case of periodicity in precipitation there was little evidence from available data that the phenomenon could be traced west of the Plains. If the pulses came from the west, as continuity suggests, the amplitude was increased in the weak United States trough. The failure to trace precipitation periodicities farther west could be due to the small amounts and infrequent occurrence of precipitation. Theoretically, the application of the fundamental Fourier Series term is best made to continuous elements, such as temperature. If, for instance, in an arid climate rain fell only on Sunday, R_{28} would be quite small despite a perfectly timed succession of pulses. Consequently, the precipitation periodicities are, other things being equal, most apt to be found where the precipitation is frequent and abundant or when an areal (rather than "pinpoint") tabulation of data is used to introduce continuity of parameter. Periodicities in meteorological elements have already been traced around the hemisphere [5] and a continuation of such studies should indicate more clearly where in the circulation pattern the sinusoidal characteristics are most marked.

In conclusion, it is obvious that 7-day periodicities were fairly common this spring. Both the April temperature at Omaha and the Washington, D. C., precipitation in May showed unusually significant persistence of weekly patterns. Whether the ultimate cause of these patterns rests in one of the natural free modes of oscillation for the atmosphere remains to be demonstrated. Currently the temperature phase preference (for Sunday-Monday) noted at Omaha is one of the most puzzling aspects of the data studied.

ACKNOWLEDGMENT

The Fourier analyses and statistical testing of the periodicities cited in the text were performed in the Meteorological Statistics Section of the United States Weather Bureau, Washington, D. C., by J. C. Coffin under the direction of G. W. Brier. The author takes this opportunity to thank them for their considerable work and advice.

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HEAVY RAINFALL OVER NORTHEASTERN WYOMING AND SOUTHERN MONTANA, MAY 21, 1952

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INTRODUCTION

On May 21, 1952, 1 to nearly 3 inches of rain fell over a narrow oblong strip of territory extending form Chadron, Nebr. to Billings, Mont. and westward to Bozeman, Mont.

Stations within the belt of heavy rainfall reported steady post-frontal type rain which continued to fall even after the cold front had moved into the eastern portions of Kansas and Nebraska. Outside this area the showers and thunderstorms ceased within a few hours after the frontal passage.

The rainfall in the Dakotas and Montana was preceded by low-level advection of moisture from the Gulf of Mexico northwestward toward the western Dakotas where it was lifted to high altitudes by a developing cyclonic circulation aloft.

SURFACE WEATHER

It was not evident on the 1230 GMT surface chart for May 20, 1952 (fig. 1) that air from the Gulf of Mexico would be drawn northward over the Plains to Montana within 24 hours. The surface pressure configurations in figure 1 suggested that the region of the northwestern Plains should be under the influence of maritime Polar air during the following 24 hours. The weak cold front which had extended southward from north-central Montana had virtually dissipated by 2130 GMT in the vicinity of Sheridan, Wyo.

With the decay of this weak front, another cold front became evident along a line from Great Falls, Mont., to Ely, Nev., at about the time the preceding one was dropped from the analysis. The second cold front was accompanied by numerous showers and thunderstorms by the time it reached western Montana, and the instability type of weather continued as the front moved eastward to the middle Plains States. At 0330 GMT May 21, considerable shower activity was in progress over western Montana when steady rains began to fall at Dubois, Idaho, and Dillon, Mont. During the following day this area of steady rain moved eastward to the location shown by figure 2, the 1230 GMT map for May 21. The cold front shown east of the Divide is the one which had taken form on the previous afternoon.

The establishment of a clearly defined flow of Gulf air moving northward over the Plains States was the most important change to take place from the 20th to the 21st. This came about because of surface deepening which, in turn, was related to increasing cyclonic vorticity aloft as an upper-level jet stream moved southeastward from the State of Washington. The steady rainfall over the Montana–Wyoming region is indicated by the shaded area on the map for 1230 GMT, May 22 (fig. 3). This figure also shows that the flow from the Gulf was still reaching the northern Plains States.

Examination of upper air charts during the period of rain shows that moisture from the Gulf was advected into the region at, or below, the 850-mb. level, whereas, the air flow at the next standard level (700 mb.) was from the west, which was also true of higher levels. It will be noted that there is a similarity between the moist flow at 850 mb., 0300 GMT, May 22 (fig. 4) and the 24-hour precipitation pattern for the period ending 1230 GMT on May 22 (fig. 5).

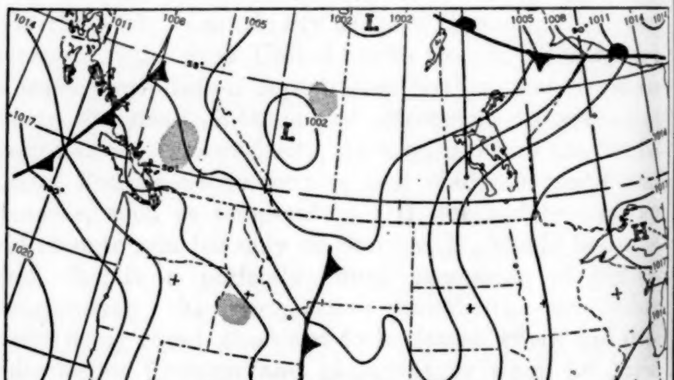


FIGURE 1.—Surface chart, 1230 GMT, May 20, 1952. Shading indicates areas of active precipitation.

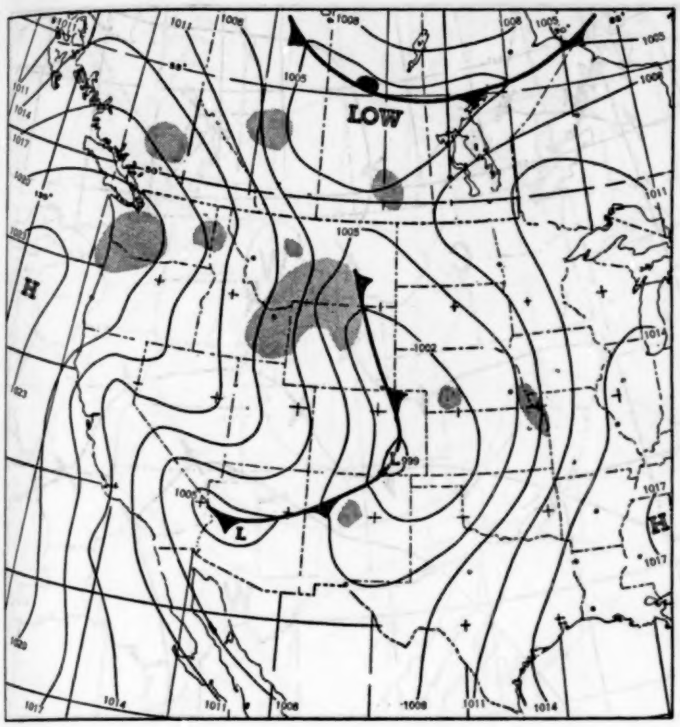


FIGURE 2.—Surface chart, 1230 GMT, May 21, 1952.

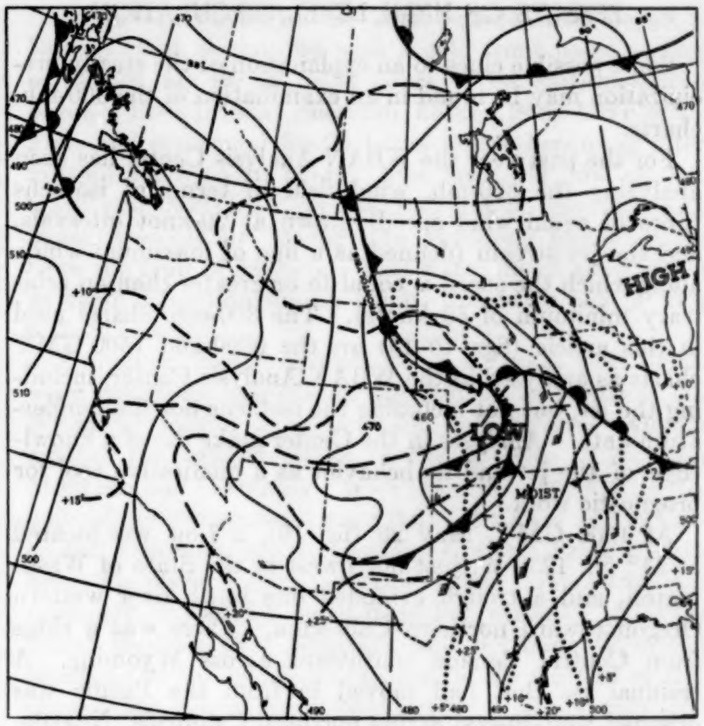


FIGURE 4.—850-mb. chart, 0300 GMT, May 22, 1952. Contours (solid lines) are at intervals of 100 geopotential feet, selected isotherms (dashed lines) at intervals of 5° C., and dew point isotherms (dotted lines) for 5° and 10°C. Barbs on wind arrows are for speeds in knots (pennant=50 knots, full barb=10 knots).

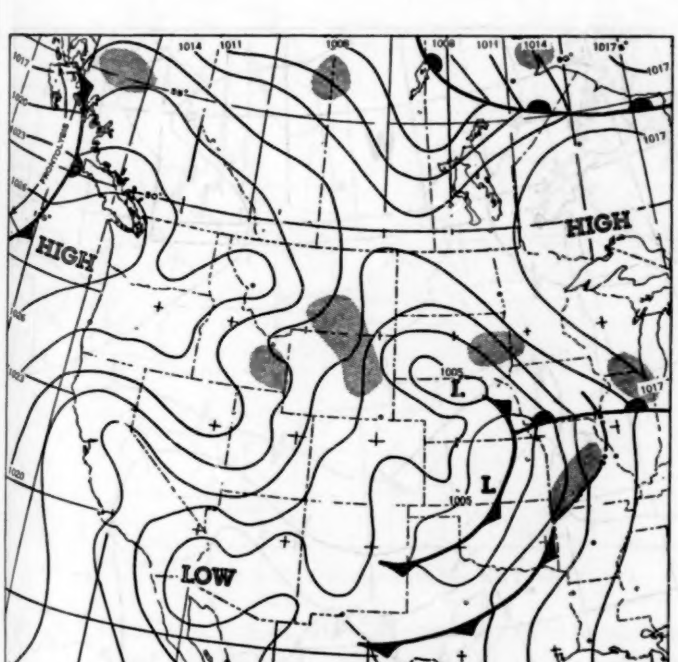


FIGURE 3.—Surface chart, 1230 GMT, May 22, 1952.

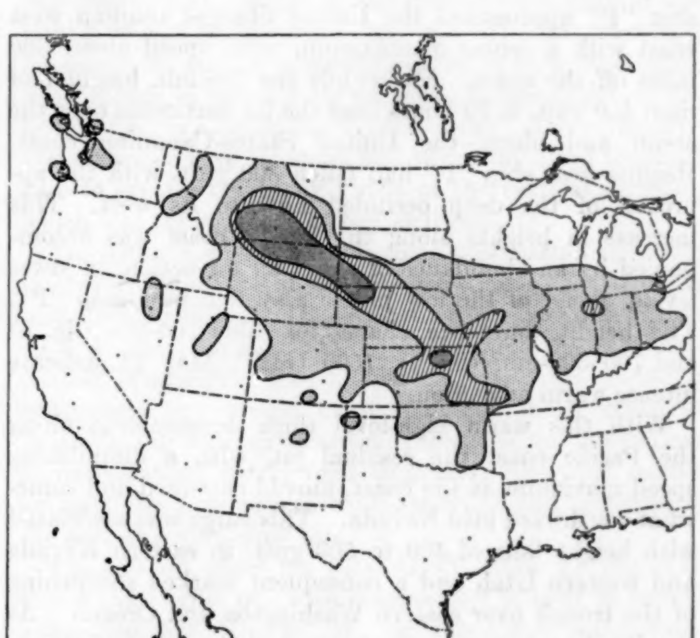


FIGURE 5.—Precipitation chart for 24 hours ending 1230 GMT, May 22, 1952. Light stipple=Trace to less than ½ in., hatching=½ in. to less than 1 in. and heavy stipple=1 in. or more.

EFFECTS OF HIGH LEVEL CIRCULATION

Some possible clues to an explanation of the steady precipitation may be found in an examination of the 300-mb. charts.

For the past year the WBAN Analysis Center has been analyzing the 300-mb. wind field in terms of isotachs (lines of equal wind speed) drawn at 20-knot intervals, and the jet stream (defined as a line of maximum winds along which the speed is equal to or greater than an arbitrary minimum of 50 knots). The 300-mb. charts used in this article (figs. 10–15) are the 0300 and 1500 GMT charts as analyzed in the WBAN Analysis Center, including the jet, but not including the isotachs nor the temperature data. Analysts in the Center make use of a knowledge of the jet and its behavior as a qualitative tool for prognostic work.

At 1500 GMT, May 20 (fig. 10), a Low was located at 51° N., 123° W. just northwest of the State of Washington, and a trough extended due south over western Oregon toward northern California. There was a ridge from Central Canada southward across Wyoming. A residual jet that had moved in from the Pacific was oriented west-to-east across northern California, Nevada, and Utah, while farther upstream, in the vicinity of stationary weather ship "P" (50° N., 145° W.), another jet was moving fairly rapidly toward the southeast. This new wind maximum was apparently associated with a rapidly occluding, deep Low at the surface about 400 miles west-southwest of ship "P".

By 1300 GMT, May 2 (fig. 11), the jet formerly near ship "P" approached the United States-Canadian west coast with a center of maximum wind speed about 300 miles off the coast. Meanwhile the 300-mb. height had risen 400 gpft. in 12 hours near the jet maximum over the ocean and along the United States-Canadian coast. Heights near ship "P" had fallen 300 gpft. with the approach of the deep occluded Low to its west. This increase in heights along the Pacific coast was accompanied by an abundance of warm air advection, in lower levels, ahead of the low pressure system near ship "P". The height difference charts for 1000–700-mb (fig. 6) and 700–500-mb. (fig. 9), 1500 GMT, May 21 indicate intense warm advection.

With this warm high-level ridge development along the Pacific coast the residual jet, with a diminishing speed maximum at the coast, moved eastward and somewhat southward into Nevada. This surge was associated with height falls of 400 to 500 gpft. in eastern Nevada and western Utah and a consequent marked sharpening of the trough over eastern Washington and Oregon. As the Pacific jet maximum approached the coast of Washington the 300-mb. low center moved into central Washington by 0300 GMT (21st) with a trough extending south-southeastward from the low center into northeastern Nevada and northwestern Utah. With this

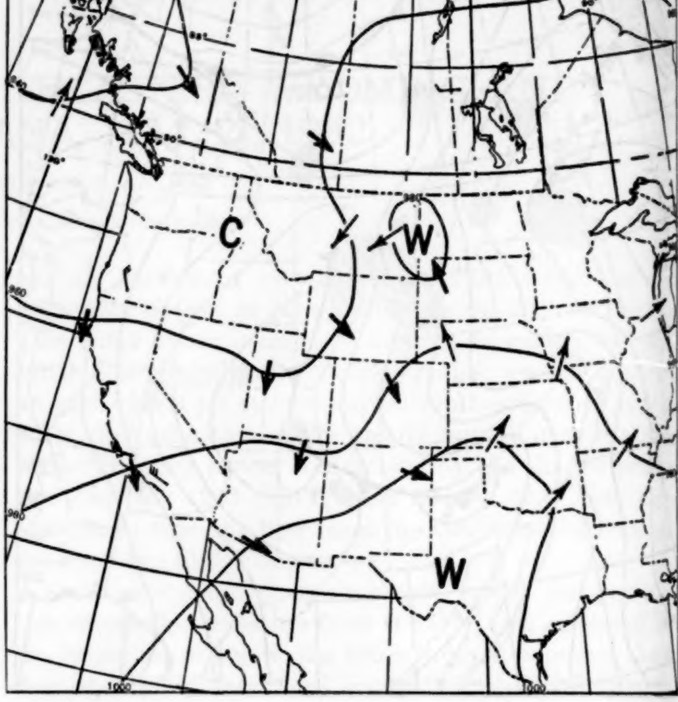


FIGURE 6.—1000—700-mb. height difference chart, 1500 GMT, May 21, 1952. Thickness isolines are drawn at intervals of 200 geopotential feet; warm air advection is indicated by thin arrows and cold air advection by thick arrows. Wind arrows show vector difference (speed in knots) between the two levels. Warm air source is indicated by "W" and cold air source by "C."

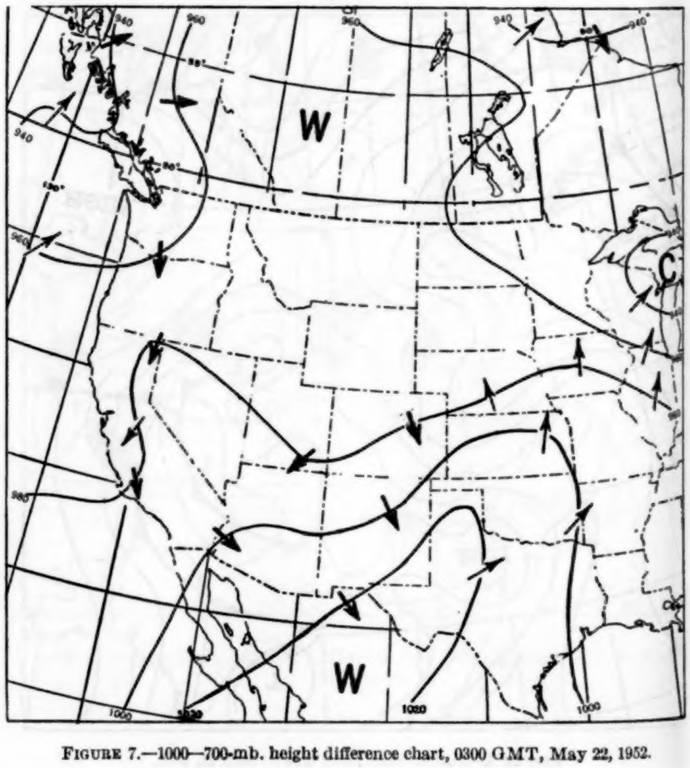


FIGURE 7.—1000—700-mb. height difference chart, 0300 GMT, May 22, 1952.

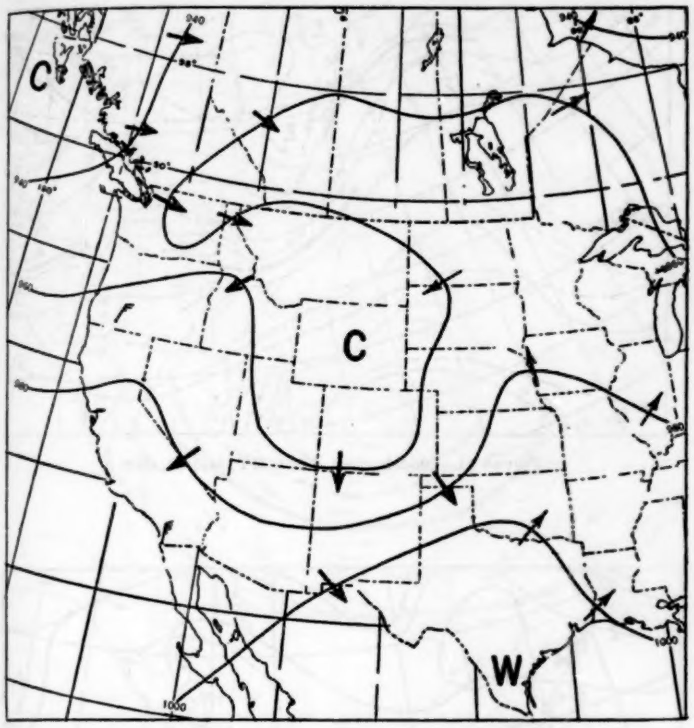


FIGURE 8.—1000—700-mb. height difference chart, 1500 GMT, May 22, 1952.

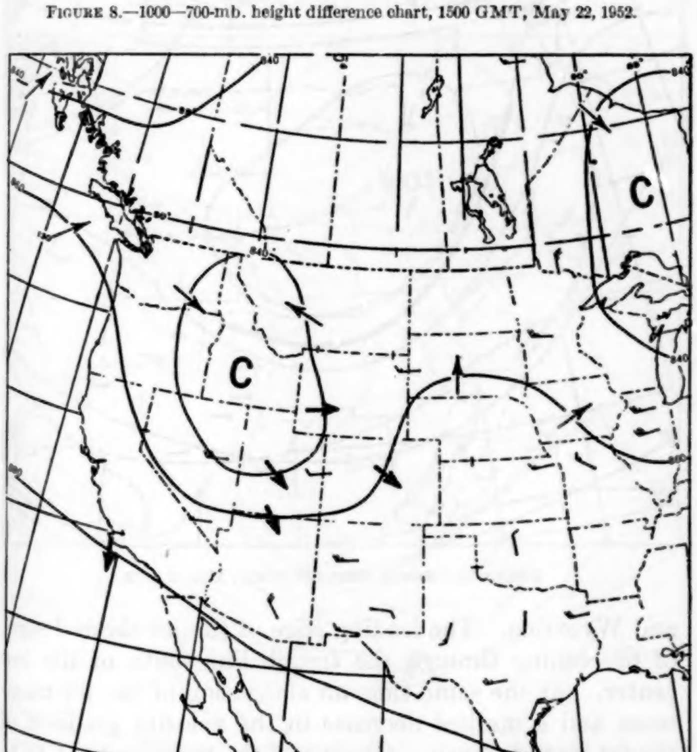


FIGURE 9.—700—500-mb. height difference chart, 1500 GMT, May 21, 1952.

development the winds over Wyoming, Montana, and Utah backed markedly to SW or WSW in conjunction with the appearance of marked diffluence of the 300-mb. contours, considering the contours as streamlines, in and to the east of the trough in northern Nevada, Utah, Wyoming, and southern Montana.

Around midnight of the 20th precipitation began at Billings, first as showers with a cold front passage, then as steady rain for 28 to 30 hours. The continuous rain began a little later at Sheridan, around 0400 MST of the 21st, and continued for 25 hours before becoming intermittent for 8 to 10 hours. The low-level flow at 0300 GMT and 1500 GMT on the 21st (fig. 5) showed warm, moist, tropical air flowing into Wyoming and Montana from the Gulf of Mexico. This warm moist air is shown as warm advection on the height difference charts (figs. 6, 7, 8, and 9).

A shallow, cool, maritime Polar air mass west of the weak cold front and east of the Rockies in Montana and Wyoming moved southeastward and became dammed against the eastern slopes of the Rockies in southern Montana and Wyoming With the southeast drift of the upper-level low center toward Salt Lake City and later to central Colorado, the warm moist Gulf air was forced up over this cooler air mass precipitating its moisture continuously just as if a warm front had existed. After the initial showers over Montana and northern Wyoming, produced by the cold front passage, hourly weather reports showed the precipitation changed to a steady rain over southern Montana and northern Wyoming during the period concerned. Showers and a few scattered thunderstorms existed throughout the period in eastern Utah and Colorado and ended as the upper-level low center moved to the east. Aloft markedly diffluent air flow existed over Montana and Wyoming (fig. 3) as the Low moved southeastward, while there was confluence evident over the central Plain States in warm south-to-southeast low-level flow east of the front (fig. 4). The low-level confluence in the stream of moist Gulf air, as suggested by the wind speeds in figure 4 for example, meant moisture was being lifted to at least the 850-mb. level. Above this level the diffluence over Montana and Wyoming lifted the moisture to greater height by virtue of the vertical shrinking which was taking place at higher levels.

The 300-mb. charts provide some explanation as to why the precipitation continued for such a long time after the cold front passage. If the low center located on the 300-mb. chart for 0300 GMT of the 21st (fig. 11) near central Washington had moved eastward, the period of continuous rain would have been cut short; however, southward or southeastward movement of the upper Low, or deceleration, would tend to prolong the time period; actually the Low moved southeastward and recurved to the east at a very slow rate.

The 300-mb. chart for 0300 GMT, May 21 (fig. 11), shows the Pacific jet (with a maximum of over 95 knots) located at 50° N. 130° W., or about 300 miles west-northwest of Seattle, Wash. After having traveled around the north end of the ridge, it began moving toward the southeast. As previously pointed out, the sharpening of the trough as the residual jet moved into eastern Nevada and western Utah was followed by diffluence at

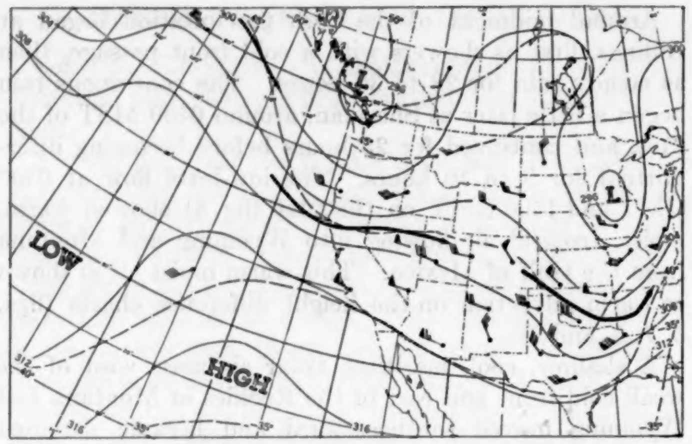


FIGURE 10.—300-mb. chart, 1500 GMT, May 20, 1952. Contours (solid lines) are drawn at intervals of 400 geopotential feet, isotherms (dashed lines) at intervals of 5° C. Barbs on wind arrows are for speeds in knots (pennant= 50 knots, full barb=10 knots). Thick black lines ending with an arrow show position of axis of jet stream.

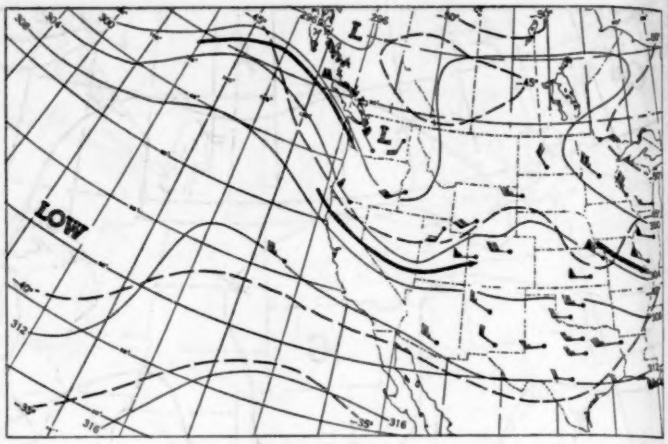


FIGURE 11.—300-mb. chart, 0300 GMT, May 21, 1952.

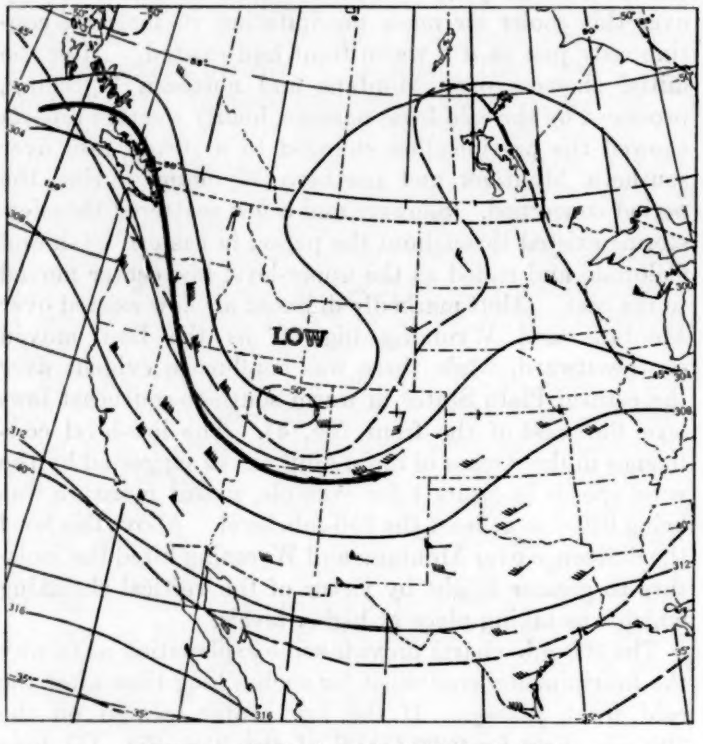


FIGURE 12.—300-mb. chart, 1500 GMT, May 21, 1952.

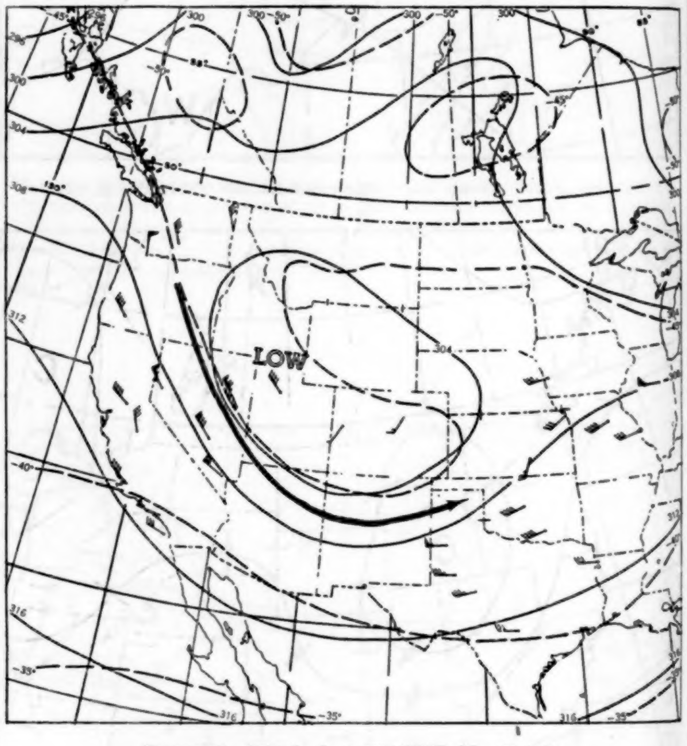


FIGURE 13.—300-mb. chart, 0300 GMT, May 22, 1952.

the trough line and eastward over Colorado, Wyoming, and Montana.

The 300-mb. chart, 1500 GMT May 21 (fig. 12), showed continued warming in the vicinity of Seattle, Wash., accompanied by a 24-hour increase in heights of 600 to 800 gpft. This increase meant a more northerly component to the winds on the west side of the trough. The Pacific jet maximum was located, approximately, over northwestern Nevada and had combined with the old residual jet. When the low center was located just northeast of Salt Lake City, weak divergence of the contours still existed due south of the Low although it was more marked in the southeastern quadrant over New Mexico, Colorado, and Wyoming. The leading edge of the jet showed signs of proceeding through the trough line south of the low center. At the same time an elongation of the jet maximum and a marked decrease in the velocity gradient of the jet was observed. Cooling of the magnitude of 4° to 6° C. occurred to the south of the 300-mb. low center as it moved toward Colorado while temperatures in the northeastern quadrant of the Low rose 3° to 4° C.

On the 0300 GMT 300-mb. chart of the 22d (fig. 13) the jet maximum was centered over north-central Arizona and was quite elongated with the leading edge overshooting the trough line and approaching the Texas Panhandle, which was under the southeastern quadrant of the Low. Height

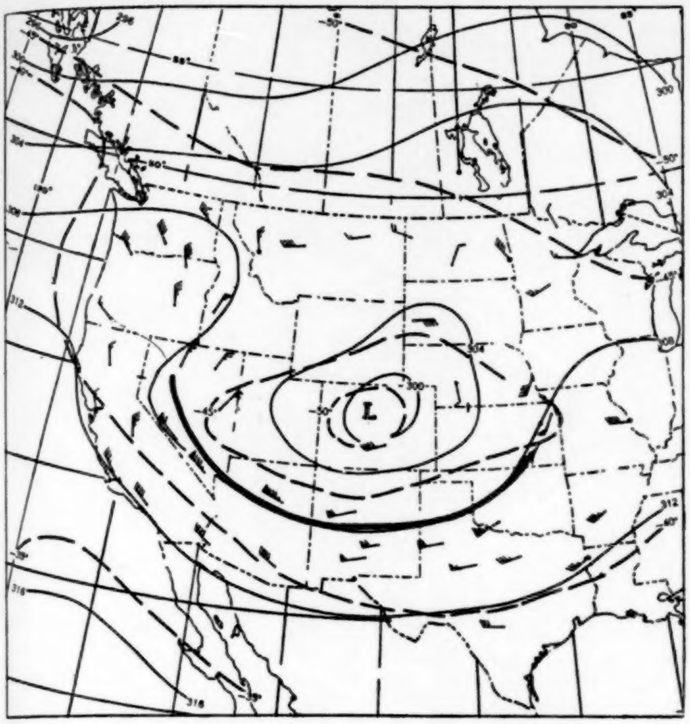


FIGURE 14.—300-mb. chart, 1500 GMT, May 22, 1952.

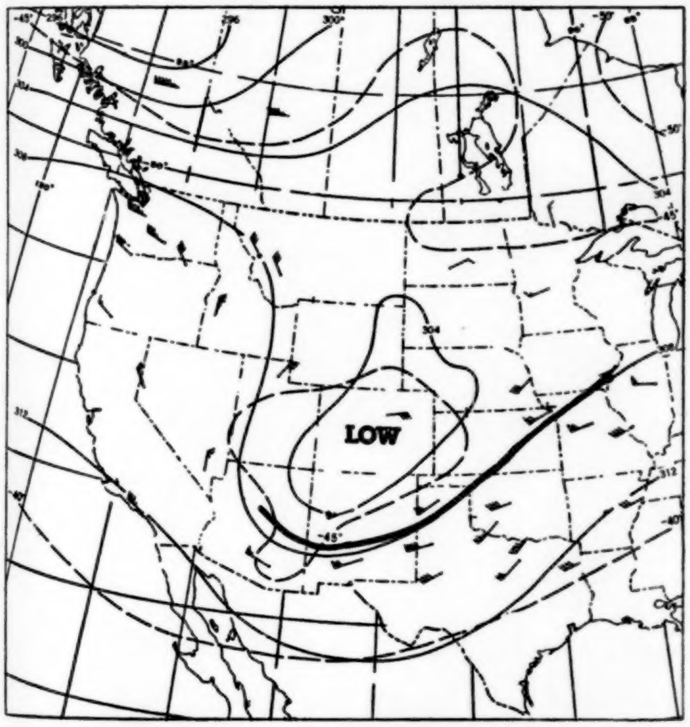


FIGURE 15.—300-mb. chart, 0300 GMT, May 23, 1952.

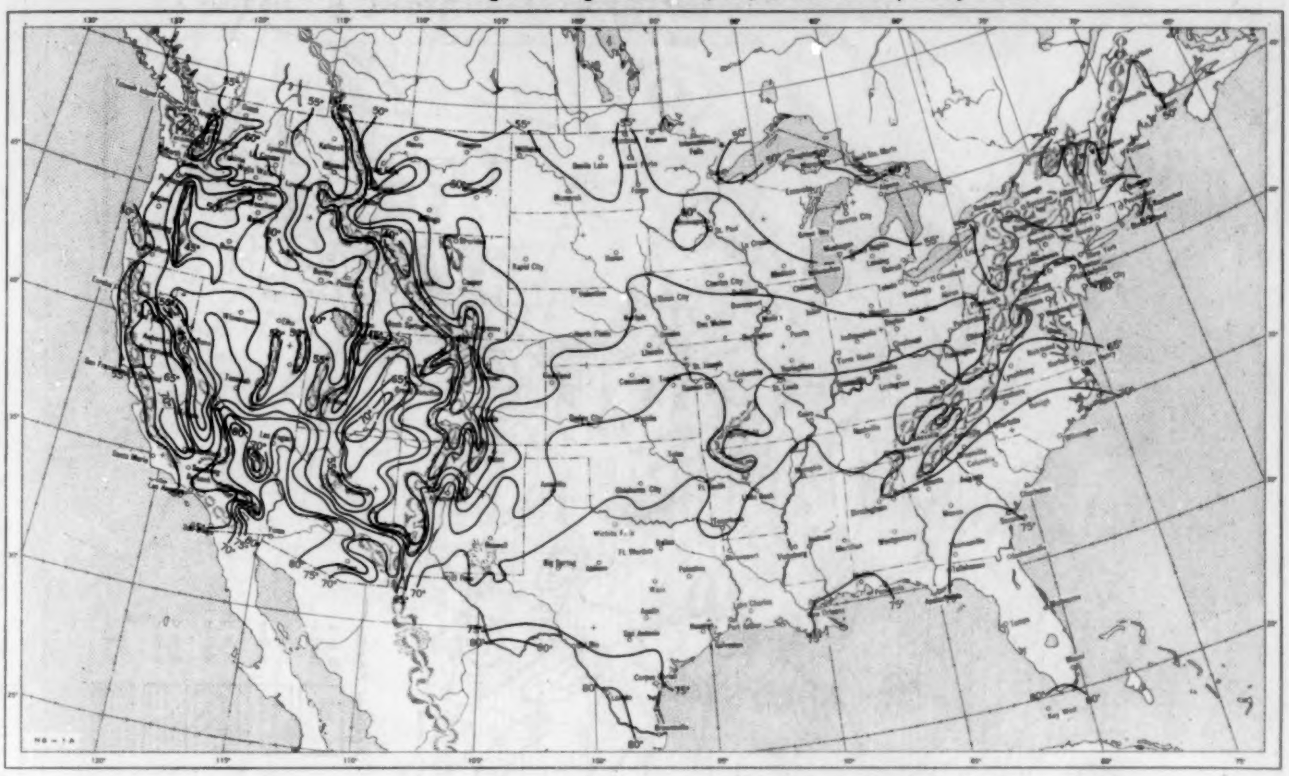
rises of 200 to 300 gpft. continued along the Oregon coastline with 500- to 600-gpft. rises north of the Low, while at the same time falls of 200 to 300 gpft. were centered over New Mexico. The contour gradient appeared equal in magnitude in the western, southwestern, and southern portions of the Low. Marked weakening of the contour gradient and light winds appeared in the northwestern portion of the Low with the spread of height rises across the northern portion of the low center. The 300-mb. low center itself, moved very slowly eastward into northeastern Utah with the leading edge of cold air at this level in western Colorado.

The 300-mb. chart for 1500 GMT of the 22d (fig. 14) shows no further southward movement of the jet, but rather a continued elongation and curving to south of the path of the upper Low. However, it was becoming more difficult to locate a jet maximum south of the low center. The Low in central Colorado moved slowly eastward across Colorado with a forward velocity of about 10 knots. The region of diffluence (indicated by the contours) had now shifted to eastern Oklahoma and extreme southeastern Kansas while marked weakening of the flow continued upstream in the western and northwestern portions of the Low. Just prior to this map time the precipitation began to diminish in southern Montana and northern Wyoming. The 300-mb. flow (fig. 14) over Montana and Wyoming suggests some convergence in the horizontal, whereas at the surface (fig. 3) this region is in an area of divergence. This is the reverse of the situation when rain fell over the sections of the two States. Once the sinking motion extended from the surface up to fairly high levels the process of vertical motion (upward) was stopped.

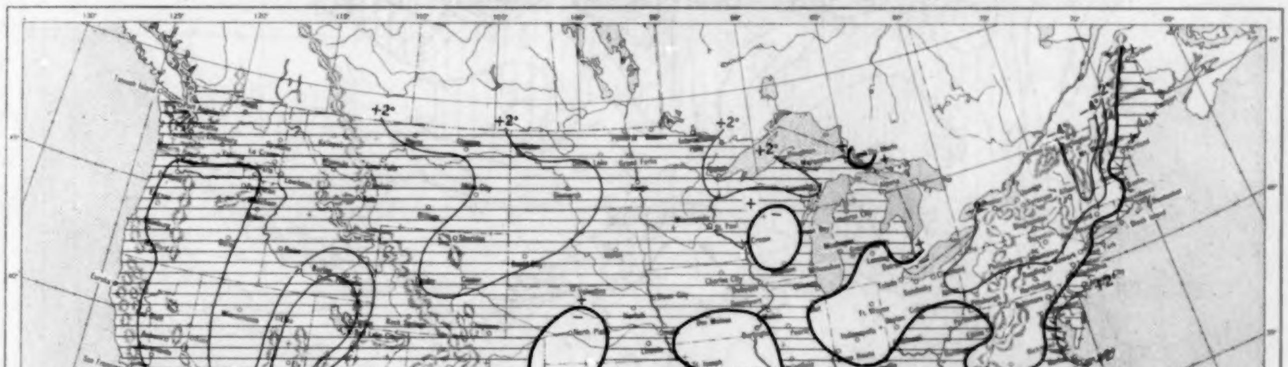
On the 0300 GMT 300-mb. chart for the 23d (fig. 15), the jet was advancing eastward into the southeastern quadrant of the Low where it assumed a southwest-northeast orientation as it moved toward the Lake region. Along with the recurvature of the jet there was also a turning of the Low toward the east-northeast. The Low also showed a slight acceleration. After the jet had passed south of the Low, the low-level flow from the south was cut off at about the time of this chart on which can be noted a filling of 300 to 400 gpft. at the Low center aloft.

At 1500 GMT of the 23d, the Low continued to fill and moved into eastern Colorado. About this time the rain, which had continued in extreme southeastern Wyoming, began to end. At 0300 GMT of the 24th, the Low at 300 mb. had filled, leaving little of its former identity in a trough over western Kansas, and the rains ended.

Chart I. A. Average Temperature (°F.) at Surface, May 1952.



B. Departure of Average Temperature from Normal (°F.), May 1952.

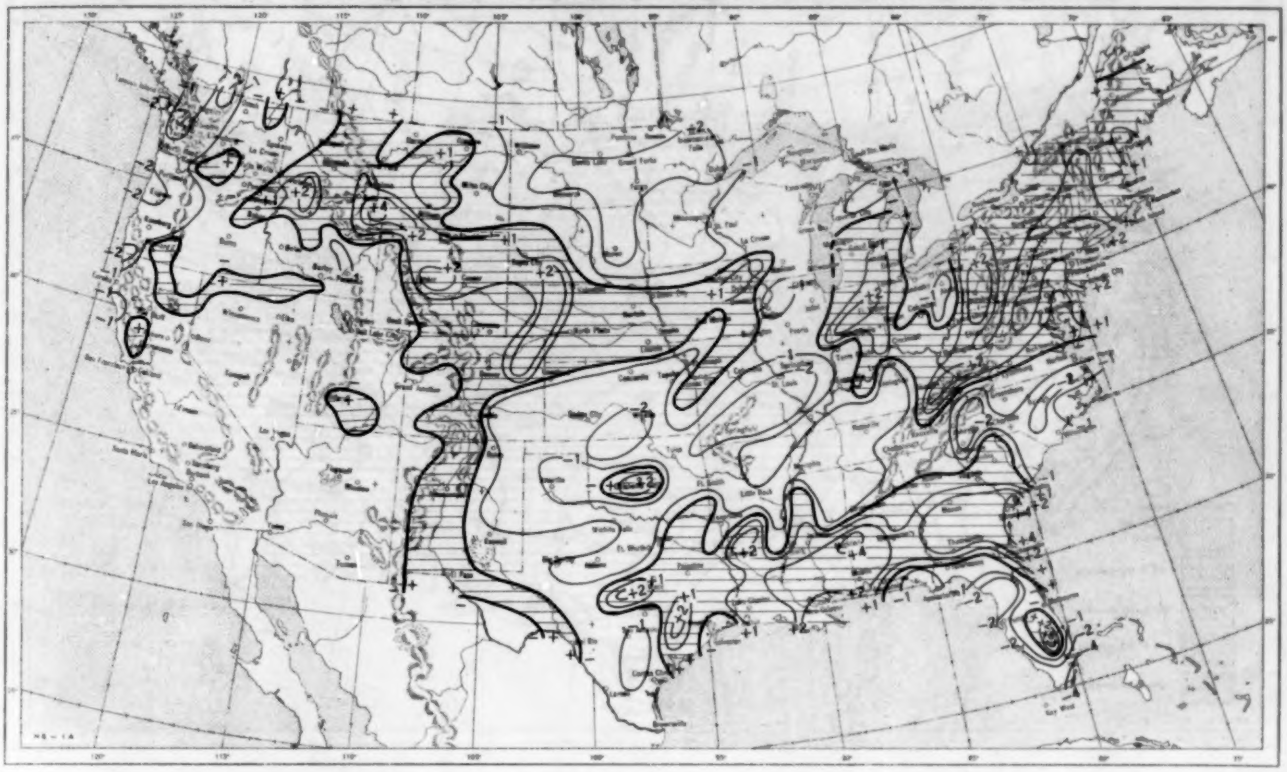


A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), May 1952.

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

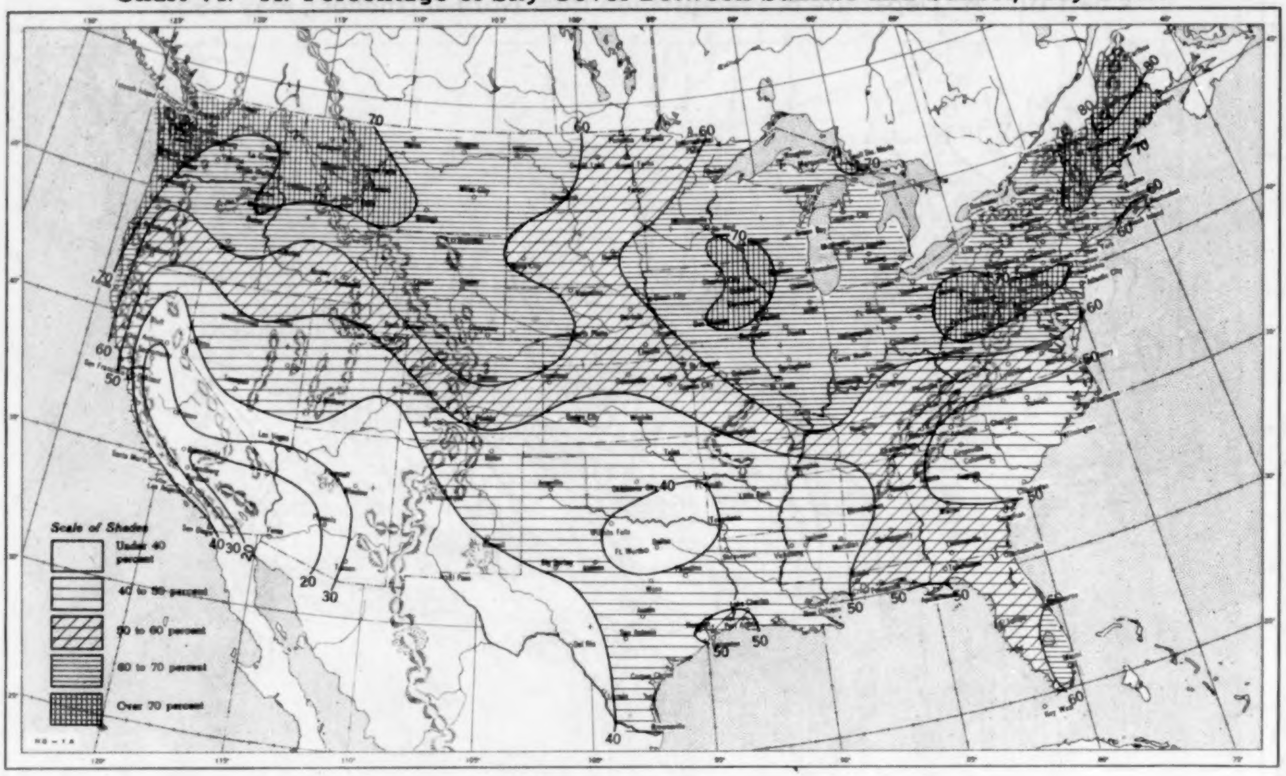
Chart III. A. Departure of Precipitation from Normal (Inches), May 1952.



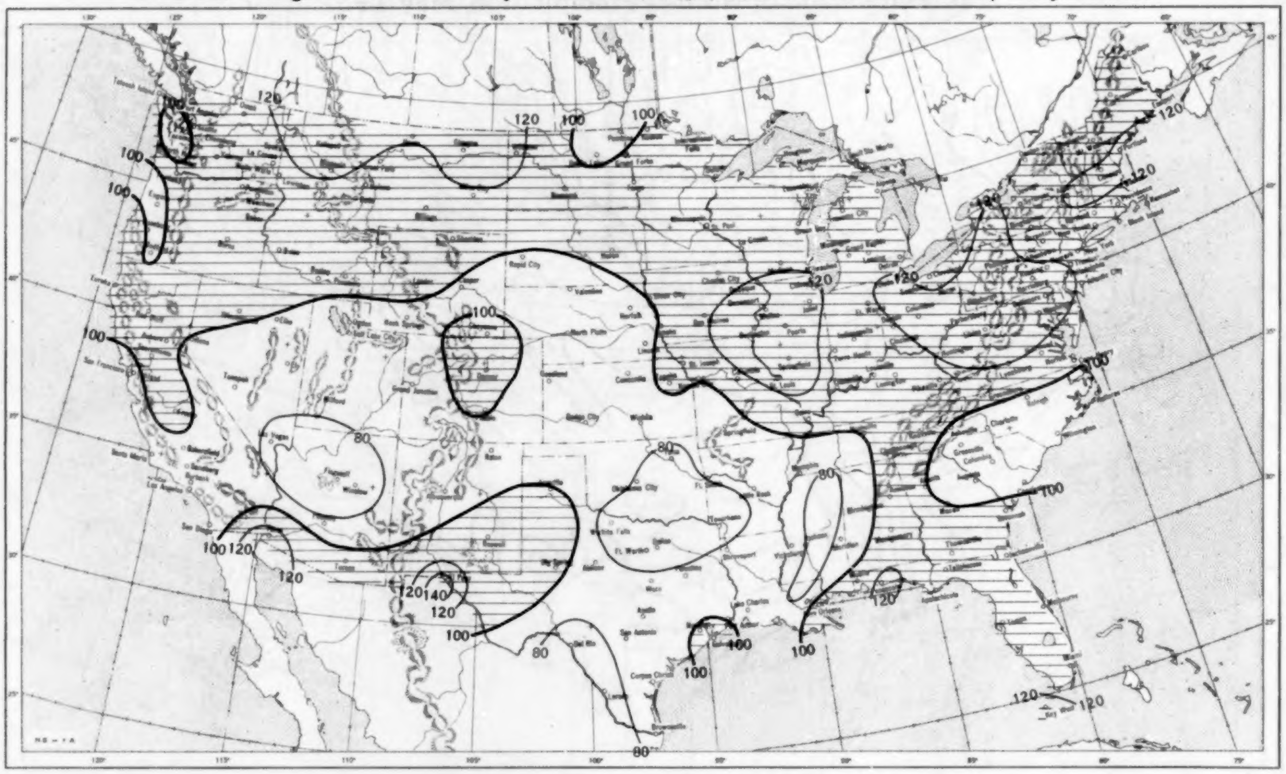
B. Percentage of Normal Precipitation, May 1952.

Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, May 1952.

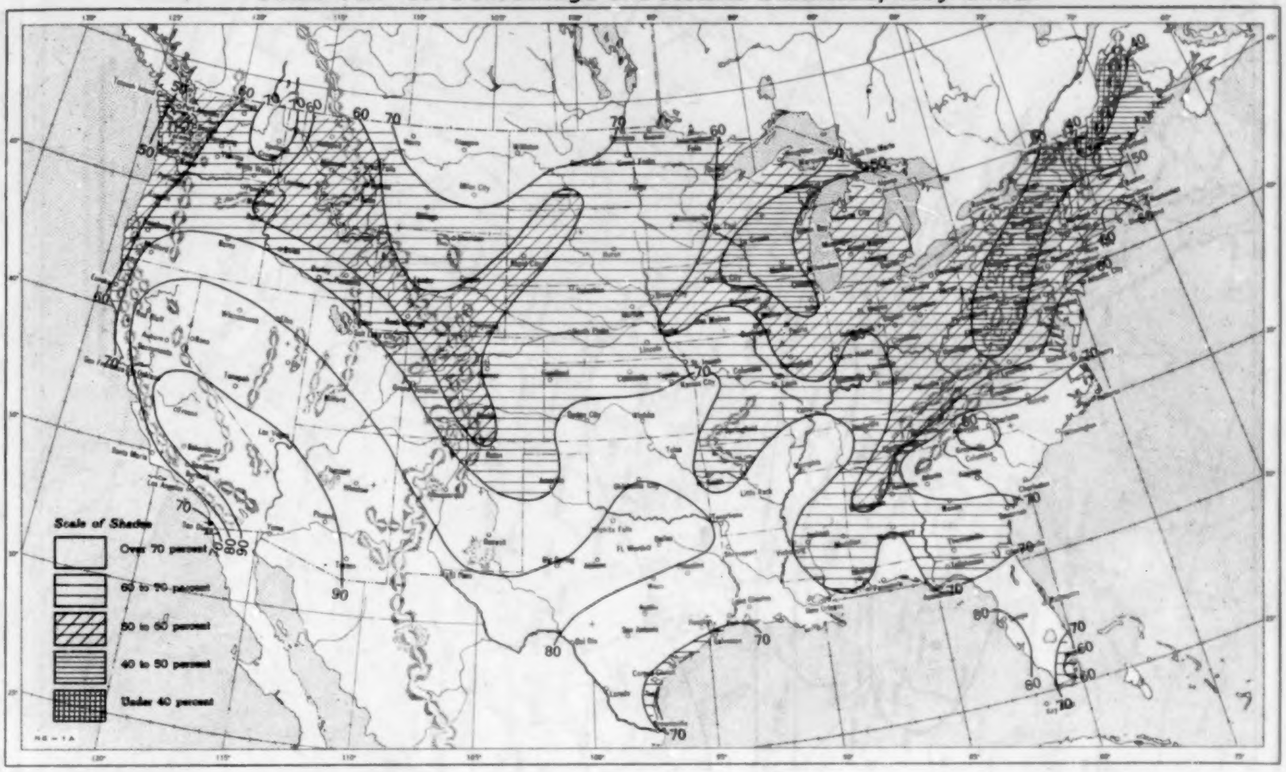


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, May 1952.

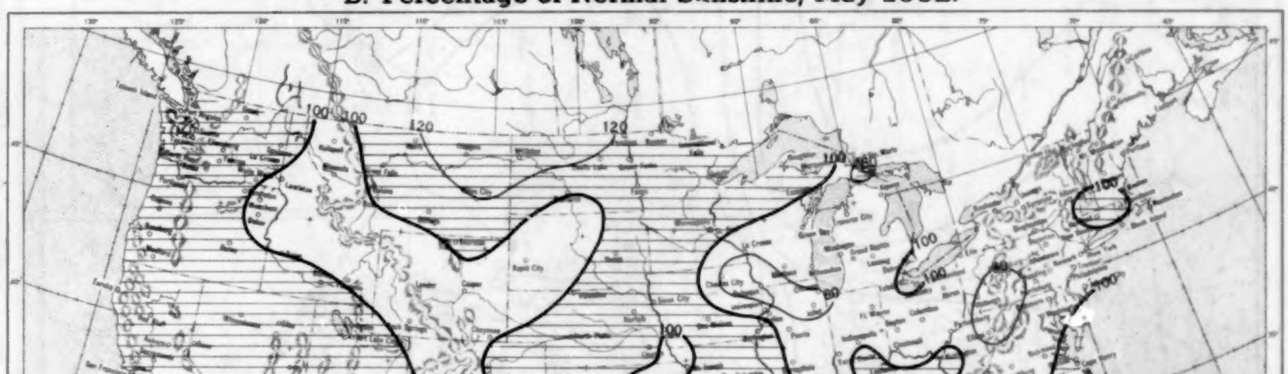


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, May 1952.



B. Percentage of Normal Sunshine, May 1952.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, May 1952. Inset: Percentage of Normal
Average Daily Solar Radiation, May 1952.

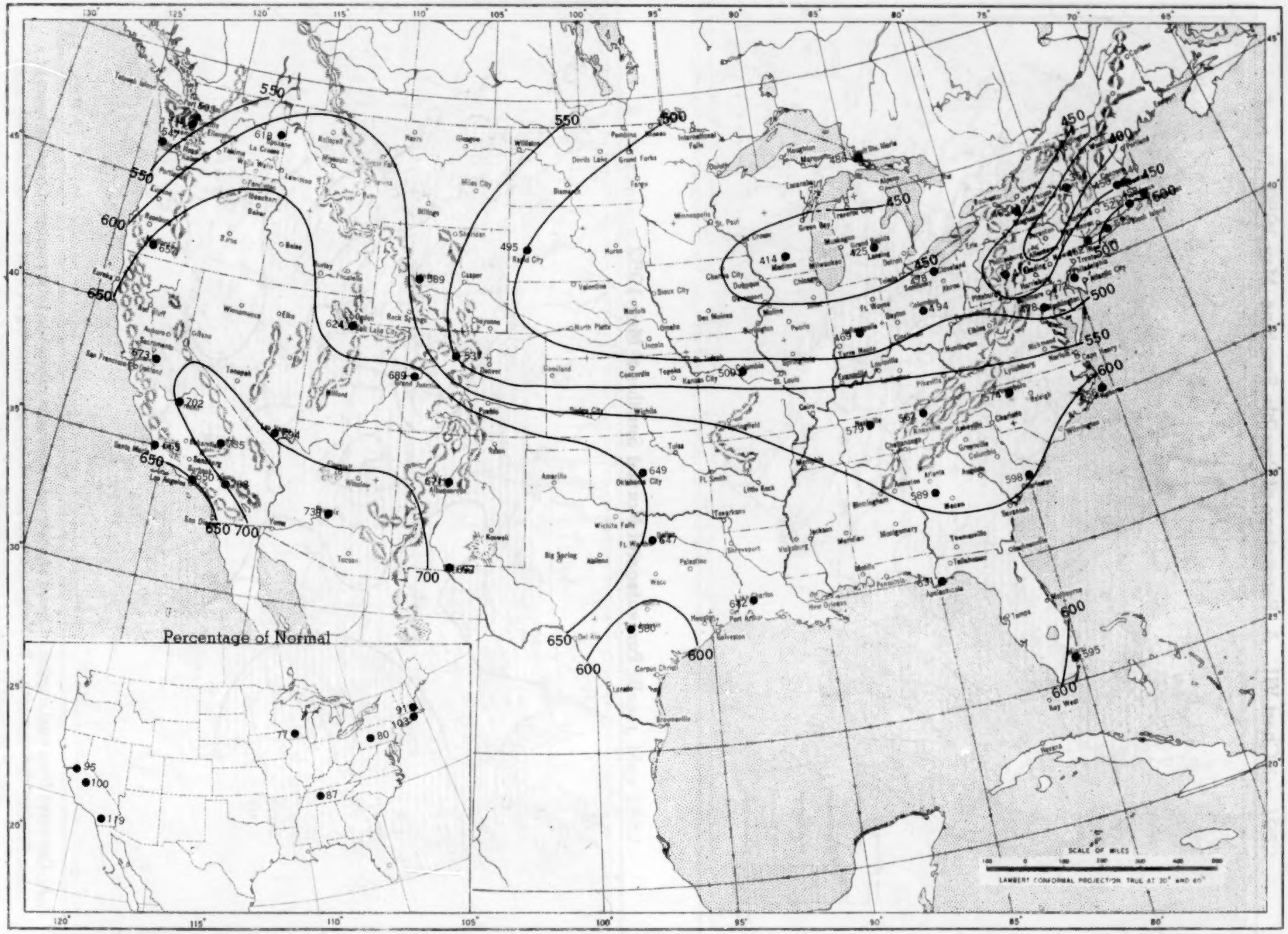
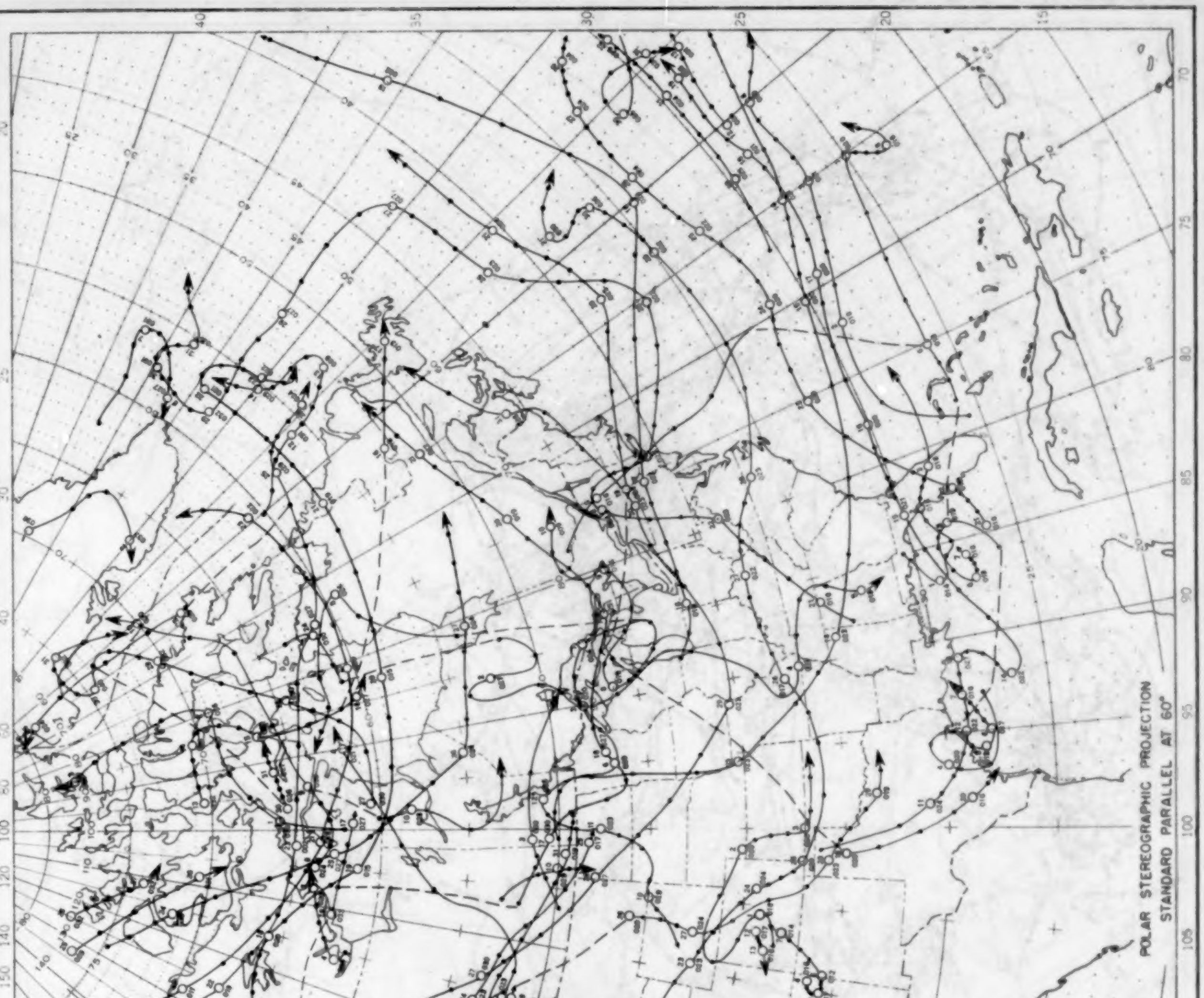


Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

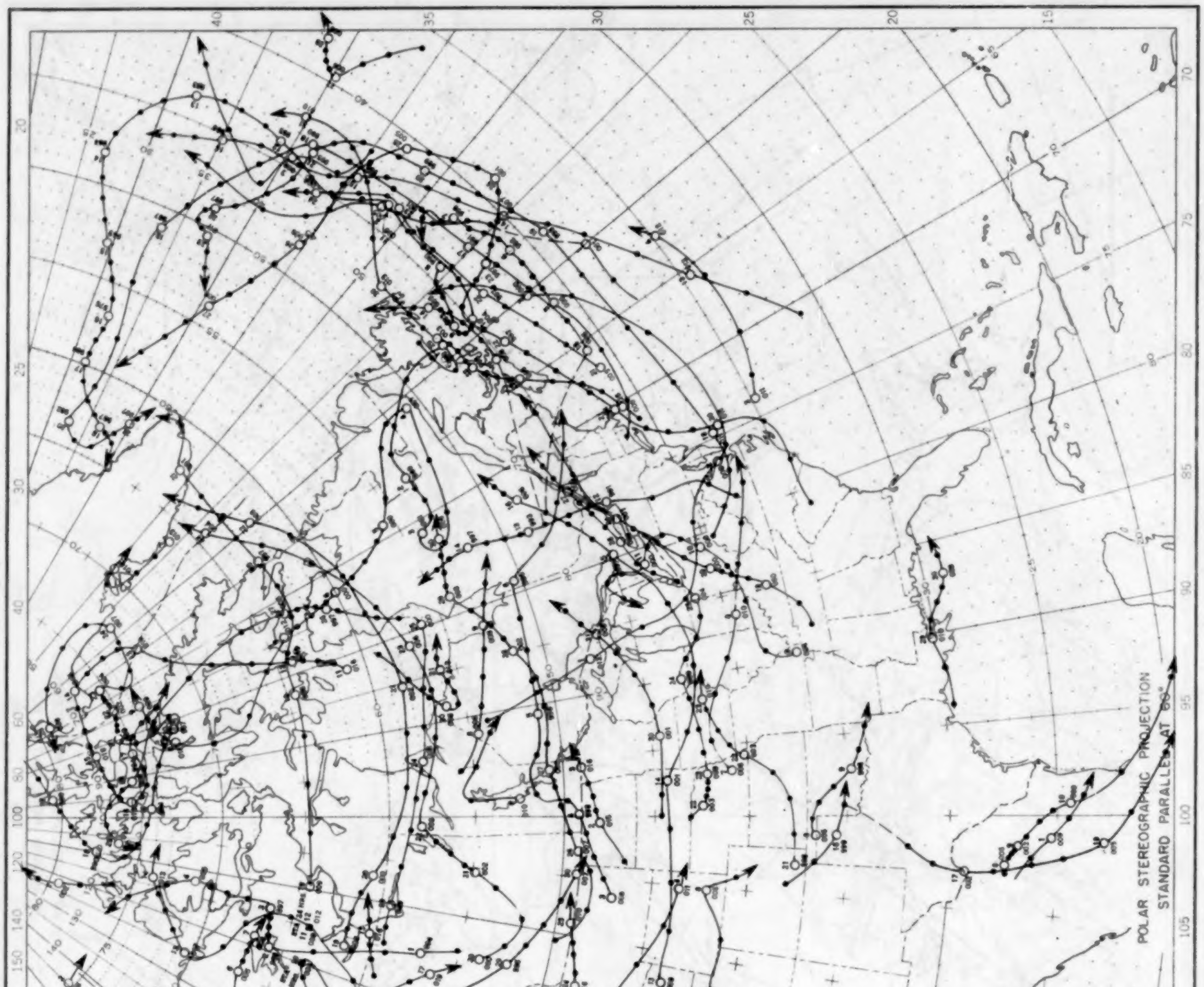
are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, May 1952.



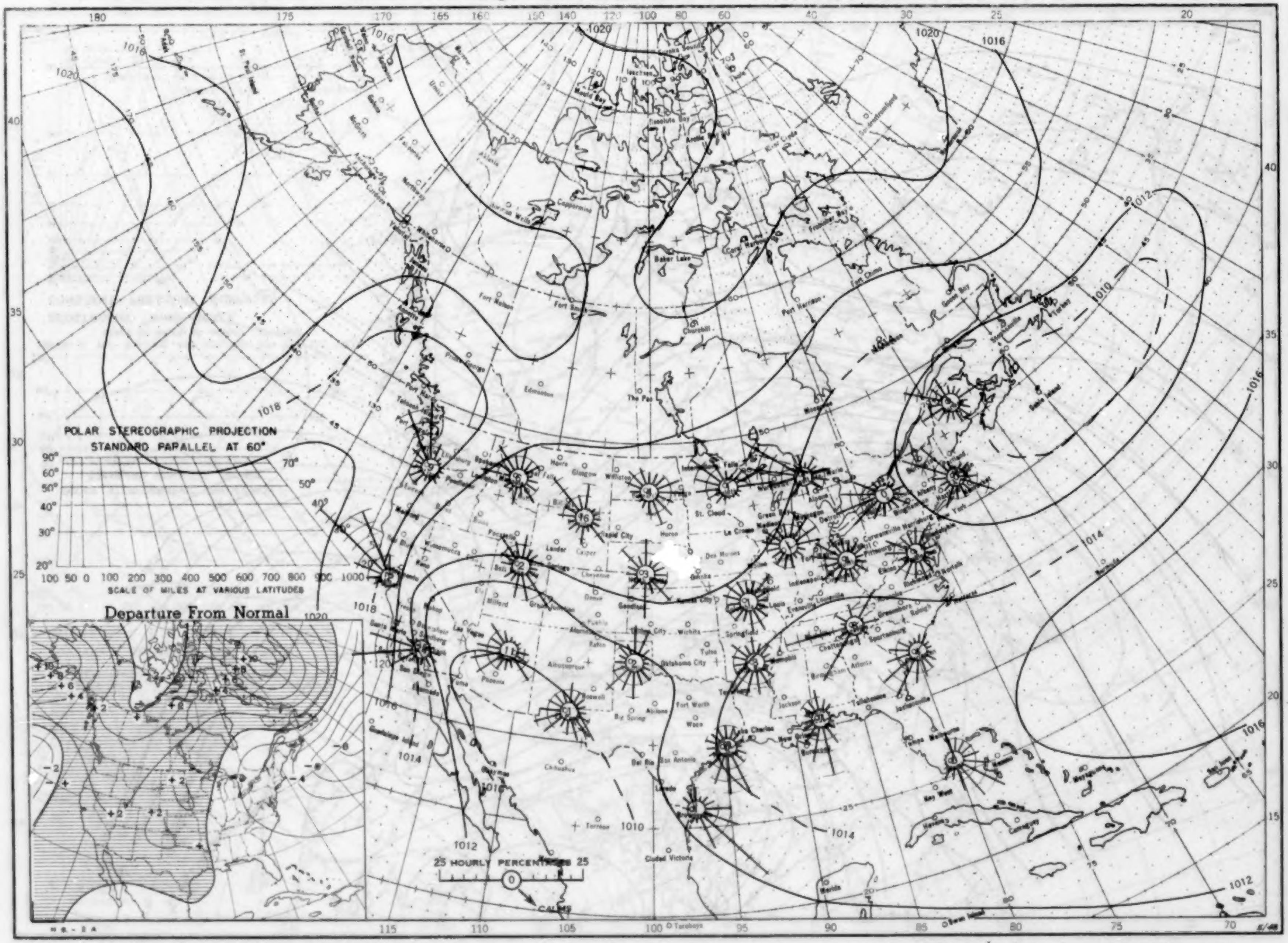
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, May 1952.



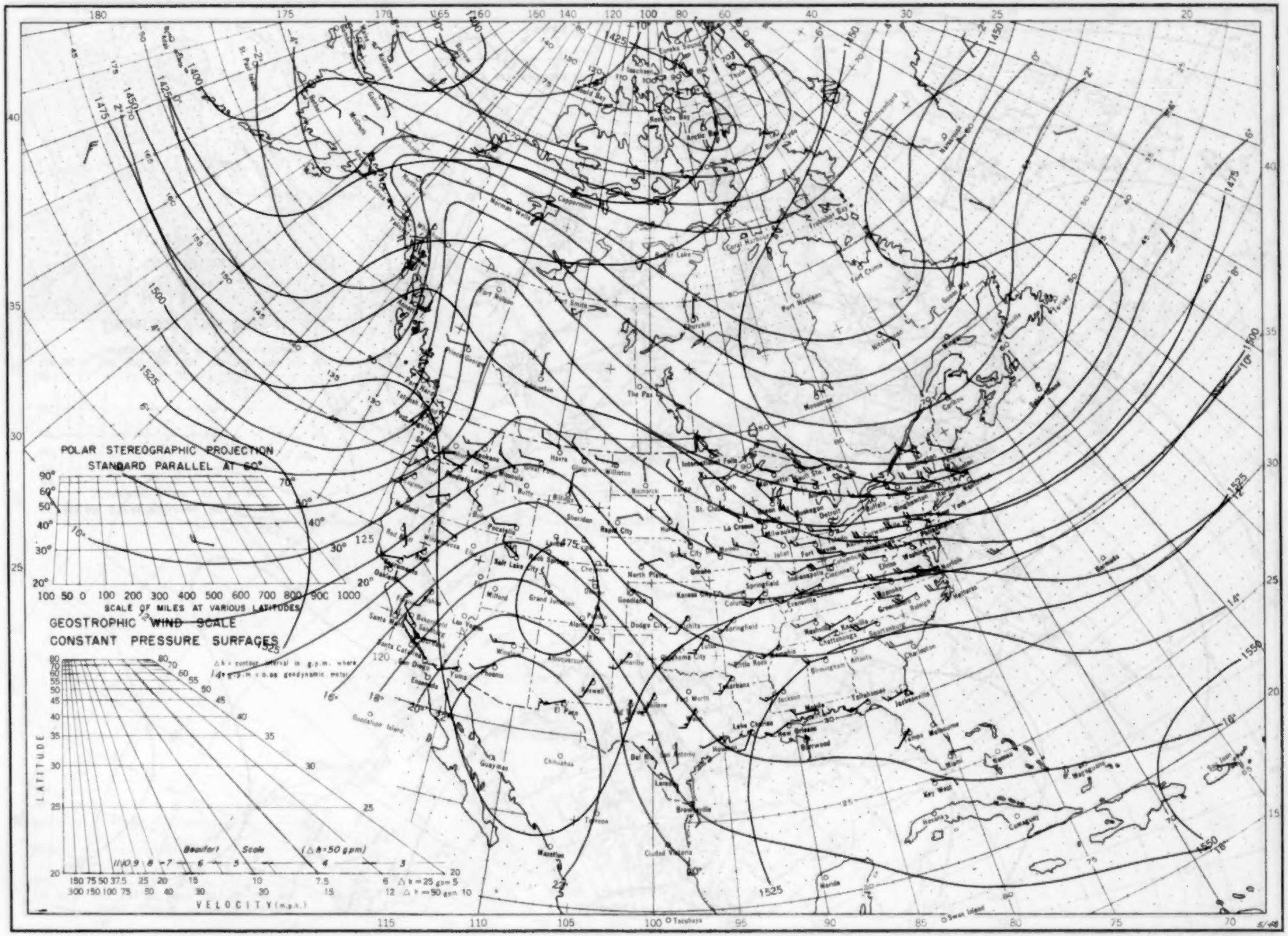
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, May 1952. Inset: Departure of Average Pressure (mb.) from Normal, May 1952.



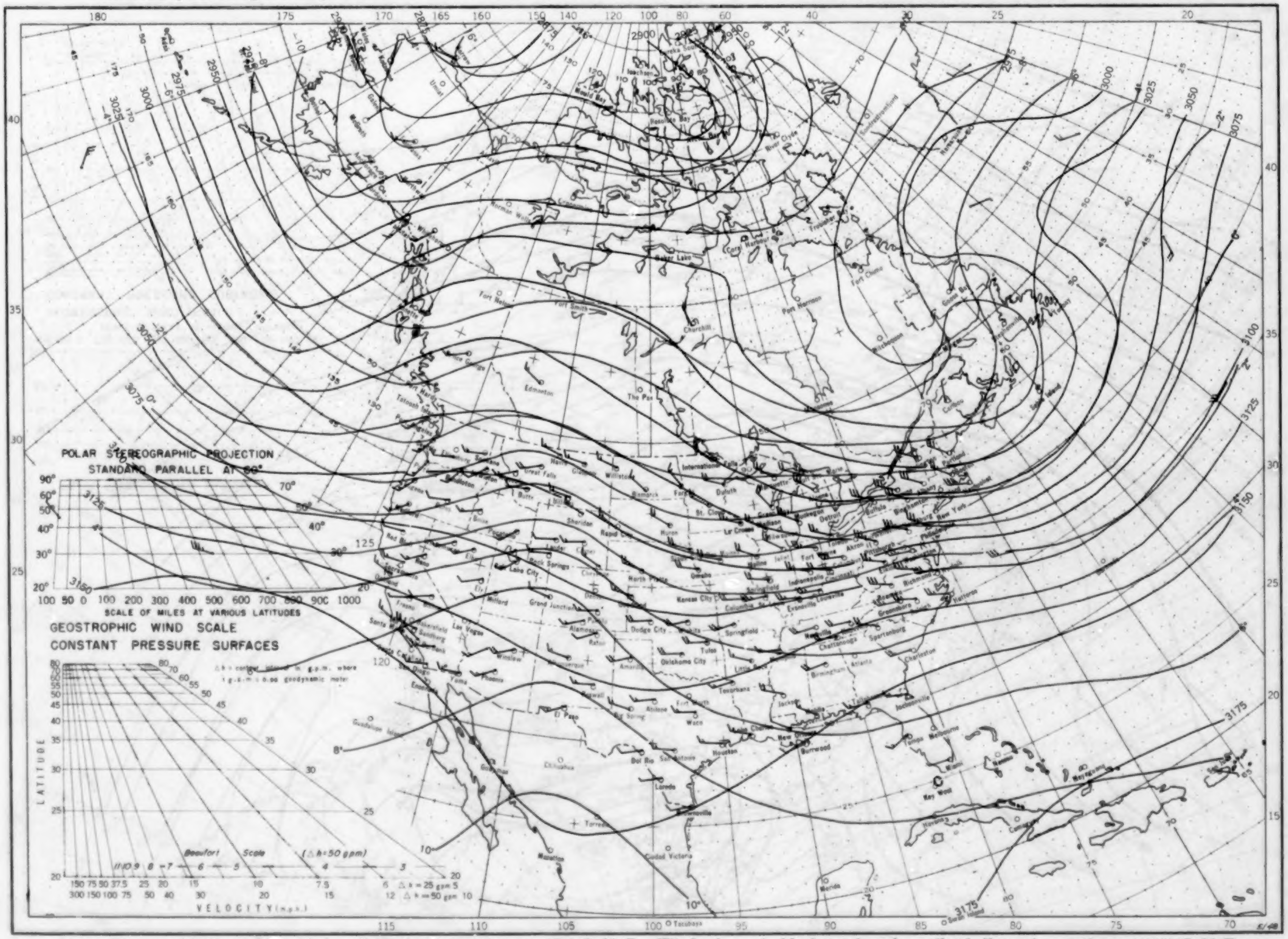
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), May 1952.



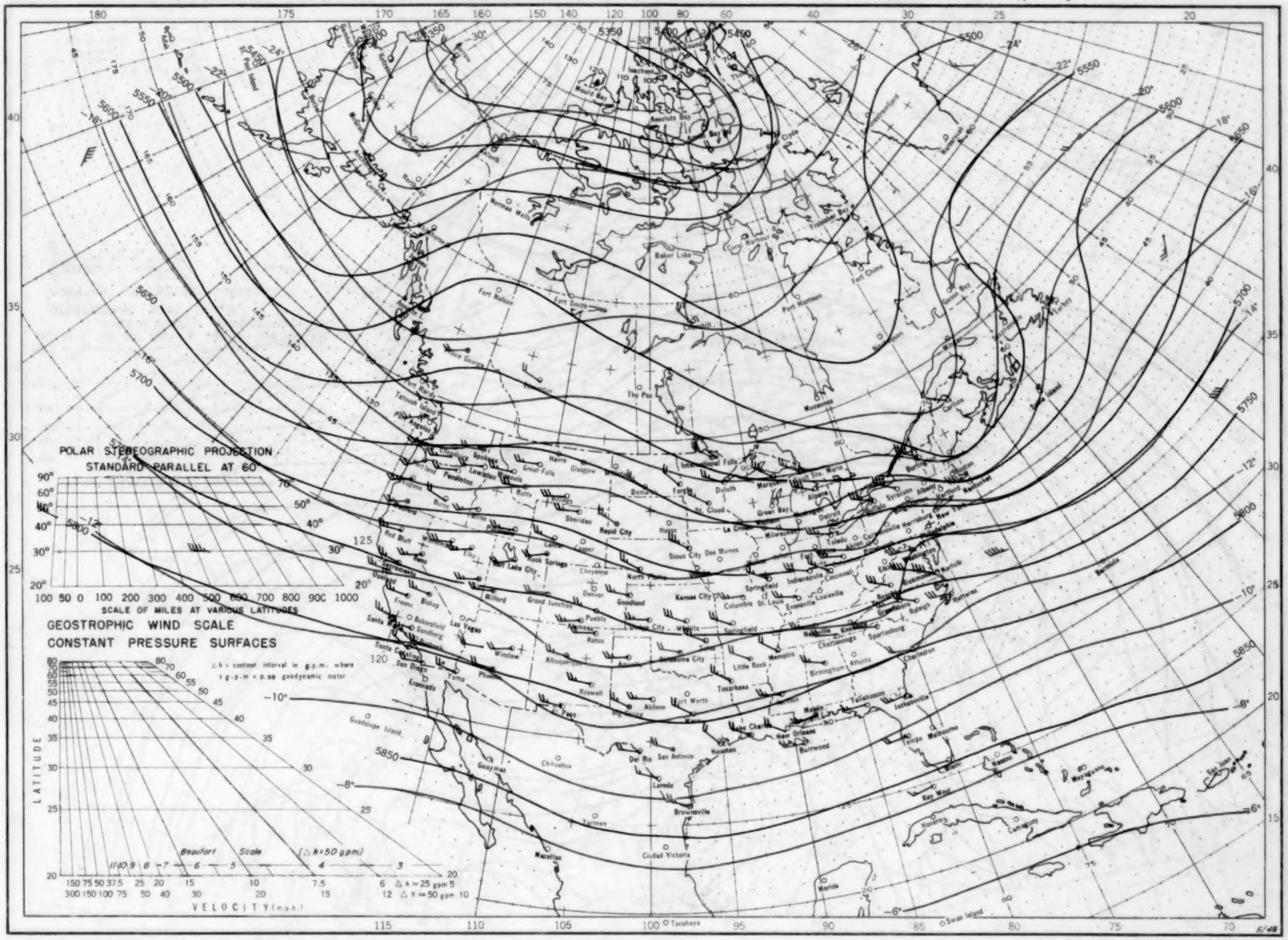
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), May 1952.



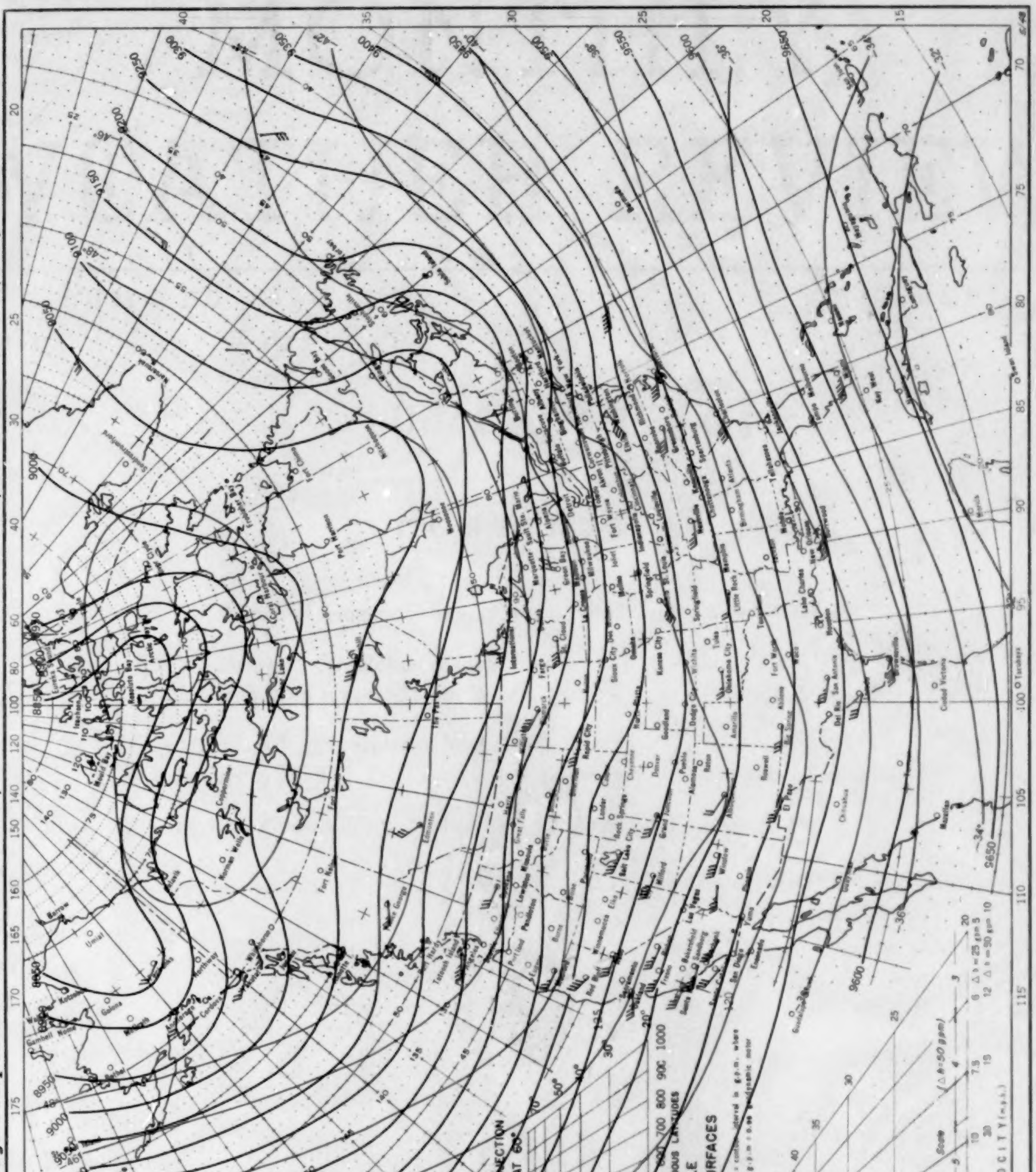
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), May 1952.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), May 1952.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.